ARPA ORDER NO.: 3520
8K10 Director's Office

R-2212-ARPA
May 1978

Pulsed-Power Research and Development in the USSR

Simon Kassel

A Report prepared for

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

Rand
SANTA MONICA, CA. 90406

The research described in this report was sponsored by the Defense Advanced Research Projects Agency under Contract No. MDA903-78-C-0189.

Library of Congress Cataloging in Publication Data

Kassel, Simon.
Pulsed-power research and development in the USSR.

([Report] - Rand Corporation ; R-2212-ARPA)
Bibliography: p.
1. High voltages. 2. Energy storage. 3. Dynamos. 4. Magnetic flux compression. I. United States. Defense Advanced Research Projects Agency. II. Title. III. Series: Rand Corporation. Rand report ; R-2212-ARPA.
AS36.R3 R-2212 [TK153] 081s [539.7'3] 78-18912
ISBN 0-8330-0029-2

Published by The Rand Corporation

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PREFACE

This report was prepared in the course of a continuing study of Soviet research and development of high-current, high-energy charged particle beams and their scientific and technological applications. It is a part of an ongoing program, sponsored by the Defense Advanced Research Projects Agency, which undertakes the systematic coverage of selected areas of science and technology in the USSR as reflected in Soviet technical literature.

The report discusses pulsed-power devices and elements, which are the basic means of energy delivery to all charged-particle beam systems. It deals mainly with pulsed-power generation, storage, and switching as the major aspects of the subject matter; other components of the beam systems, such as beam generators, accelerators, and handling systems, are dealt with only as necessary to provide a proper context for the discussion of pulsed-power applications.

The report also includes a discussion of the organization and planning of Soviet research and development of pulsed-power technology, as well as the detailed technical coverage of theory, testing, and operation of the pulsed-power equipment. The report is based on Soviet materials published since 1960.

SUMMARY

A comprehensive study of Soviet open-source technical literature indicates that the Soviet Union is engaged in a major effort to develop pulsed-power systems. The principal objectives of this effort appear to be (1) the achievement of controlled thermonuclear reactions as a national energy source and (2) military applications. The latter objective is evident from the determined search for higher output energies, from the drive to reduce the size and weight of the pulsed-power equipment apparent in every advanced area of pulsed-power research, and from the variety and scope of Soviet efforts, which are well beyond today's requirements for fusion research.

The organizational structure of Soviet pulsed-power R&D, involving the Academy of Sciences, branch institutes, and industrial plants, indicates the national importance of this work, considered a component of the national energy-development program. The Soviet pulsed-power R&D has been gathering momentum since the mid-sixties, when intensive programs were begun in such research areas as magnetic flux compression, superconductive inductive storage, and rotating electric machines. The intensive development of opening and closing switches for use in induction storage systems and pulse-forming networks, currently the largest research area, began in the early seventies. A significant feature of these programs is the unusual degree of cooperation among various research organizations, which appear to have formed several groups dedicated to a number of specific research areas.

The main goal in the development of magnetic flux compression devices is the production of megagauss fields. A major investigator, G. A. Shneyerson of the Department of High-Voltage Engineering, Leningrad Polytechnic Institute, obtained a field of 3 MG. The same results were obtained by G. I. Budker and S. G. Alikhanov of the Institute of Nuclear Physics (NPI) in Novosibirsk.

A. I. Pavlovskiy, in similar experiments, obtained 1.9 MG from a 1.35-MJ capacitor bank. The efficiencies (ratio of liner kinetic energy to capacitor bank energy) obtained by all of the above experimenters were about 25 percent. The suitability for controlled

thermonuclear reactions (CTR) of the open-pinch-with-liner systems used in these experiments appears doubtful because of the high requirements for stored energy (10^9 J). The Soviets, nevertheless, are proceeding with this work, now concentrated at the Yefremov Institute, where they are developing inductive storage units of the order of 20 MJ.

Budker and the Institute of Nuclear Physics in Novosibirsk appear to be the driving force behind most of the work on magnetic flux compression, both of the electromagnetic and chemical explosive types. The target of this work is the power supply to high-current charged-particle accelerators and the minimization of accelerator weight and dimensions. The R&D work in chemical explosive flux compression is being performed by Ye. I. Bichenkov at the Institute of Hydrodynamics in Novosibirsk. After ten years of research, NPI scientists were confident enough to consider the explosive magnetic generators ready for practical application in 1973.

In terms of active research workers, the area of superconductive energy storage, including inductive systems and rotating machinery, amounts to about 14 percent of the total core institutes in pulsed-power R&D covered in this report. The Institute of High Temperatures (IVT), recognizing at the time of its inception in 1962 the need for the large-scale development of superconductive inductors, established a Department of Applied Superconductivity to research and develop high-power pulse sources as one of its major goals.

The thrust of R&D work in superconductive inductors parallels that evident in the other areas of pulse power: minimization of size and weight of the components. Another objective is operational reliability of the superconductive windings. These goals are significant in view of the IVT claim that 10^9-J storage inductors are being built at this time. The requirement for 10^8- to 10^{10}-J storage inductors was also recognized by the Yefremov Institute, which is engaged in parallel work on superconducting inductive storage.

A related effort is the development of homopolar machines and multipolar pulse generators, primarily at the Moscow Aviation Institute and the Tomsk and Leningrad polytechnic institutes. The aim of this effort is to develop the power supply to high-magnetic-field devices.

The most exotic ideas in the Soviet pulsed-power field are being developed and pursued jointly by a group of researchers at the Kurchatov Institute of Atomic Energy and the Institute of High Temperatures. This group is working on various aspects of pulsed-power generators based primarily on explosive and nuclear magnetohydrodynamic (MHD) principles; it expects with these devices to achieve unprecedented output performance. The group's theoretical work is to a large extent aimed at showing that the theoretical limits (established by Western researchers) of energy and power that can be developed by pulsed MHD generators are invalid. To judge from the published reports, the Soviet experimental work, involving the testing of prototype devices using superconducting windings and chemical high explosives, was modest in scale and characterized by rather low efficiencies. In the opinion of its researchers, however, the work established the practical feasibility of such systems. The group also proposed advanced fusion and fission MHD generator systems. The explosive MHD generator driven by thermonuclear energy would deliver 10^{11} J at 10 GW per pulse. The induction-type MHD generator coupled to a fission reactor would deliver 500 MW.

The subject of switching in pulse-forming networks appears to involve the largest proportion of researchers: Over 40 percent of all authors who published papers in the pulsed-power field wrote on switching. Soviet switch designs, particularly those intended for application to inductive storage, are characterized by extensive variety and originality of design solutions. One of the more interesting opening switches, which is being developed by the Yefremov Institute in cooperation with the Leningrad Polytechnic Institute for 10 MeV and 500 kA, uses a field-emission diode as the switch element. The switch is repetitive, and its prototype withstood 1000 shots without deterioration.

The Tomsk Polytechnic Institute has developed a 1-MeV closing switch with a 2-nsec jitter that withstood 2000 shots. Other switches developed at this institute for energies up to 250 kV withstood 10^6 shots. Still other designs of interest are based on mechanical actuation principles and driven by high explosives.

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FIGURES

TABLES

SYMBOLS

B = magnetic field intensity

E = electric field intensity

I = current

j = current density

M = mach number

n = transformer turn ratio

n_e = electron density

n_i = ion density

R_e = Reynolds number (hydrodynamics)

R_m = magnetic Reynolds number

T = temperature

V, v = velocity

ε = dielectric constant

μ = magnetic permeability

σ = electric conductivity

I. INTRODUCTION

The increasing research and development of high-energy density devices, such as lasers and high-current charged-particle accelerators, and their broadening technological application require the concomitant development of power-conditioning equipment to supply these devices with the necessary energy. The technological applications of high-energy-density devices include some advanced concepts whose practical realization is a matter of the distant future; such concepts range from inertial fusion for power production, through the generation of intense microwave beams, to directed-energy weapons. Invariably, the realization of these concepts will depend, first of all, on the attainment of adequate energy levels and on the conditions of energy delivery. It is the task of the developers of pulsed power to satisfy these requirements.

The Soviet Union has shown a high degree of interest in these areas, particularly in the generation and application of high-current electron beams, where there has been a continuing effort to reduce the size of the equipment and to improve its operating characteristics. This effort places a premium on inductive storage systems in preference to conventional capacitor banks and promotes the investigation of new original principles and designs.

This report deals primarily with power-conditioning systems, excluding the conventional primary sources of energy. Reflecting the current trends in Soviet R&D, it also excludes large capacitor banks, focusing on magnetic flux compression by either electromagnetic or chemical explosive means, pulsed MHD generators involving superconductive magnet systems and nuclear energy sources, superconducting inductive storage, homopolar and multipolar pulse generators, and advanced switching systems.

The purpose of this report is to describe Soviet pulsed-power activity in depth. For this reason, the input data have been analyzed on two levels. First, the institutional and organizational relationships in this area of Soviet R&D are traced in some detail to display the individual R&D projects in the broadest possible context. Second,

the major R&D projects are analyzed technically to present significant theoretical and experimental results, achievements, and problems. It is hoped that both levels together will add up to a more systematic account of Soviet work in this area and thus will help place new Soviet developments in proper perspective.

It should be noted that this report is not intended as a comparison of Soviet and U.S. or Western research in pulsed power, but as a treatment of the Soviet state of the art and effort level and as an aid in assessing the Soviet capability to achieve the technological goals of pulsed power. It is hoped also that some of the technical discussions included in this report may prove of value to U.S. researchers.

The principal source material used in this report is the Soviet scientific and technical literature published during the past 15 years. This literature is extensive in the area of pulsed power and its applications, such as charged-particle accelerators. For this reason, it was necessary on occasion to decide somewhat arbitrarily the pertinence of certain Soviet developments to the subject of this report. Nor is the coverage of pertinent subject areas to be considered exhaustive. To keep the input material within manageable limits, only what are considered the core institutes and personnel engaged in Soviet pulsed-power R&D are treated in detail. These core performers alone, however, provide a good qualitative sense of the extent and comprehensiveness of the Soviet effort in this area. Although not the only developers of pulsed-power devices in the Soviet Union, they constitute the principal investigators of the major R&D projects and thus can be regarded as valid indicators of the level of effort and quality of achievement typical of the Soviet pulsed-power program. To supplement the organizational context, Appendix A lists pulsed-power facilities and staff authors by group, institute, and subject area; Appendix B lists in alphabetical order the known Soviet research personnel in each subject area discussed in the report.

II. ORGANIZATIONAL ASPECTS OF SOVIET PULSED-POWER R&D

The bulk of Soviet research and development of pulsed-power systems, as defined for the purpose of this report, falls within the purview of a number of institutes under the Academy of Sciences and its departments and a few independent institutes. A relatively small portion of this work is carried on at the research facilities of higher education institutions (VUZ), mostly in close association with one or another major institute of the Academy. The Academy thus appears to have a controlling role in the overall R&D work on pulsed-power systems in the Soviet Union.

The Academy of Sciences regards pulsed power as a component of the national program for the development of electric energy, which in turn, falls within the mandate of the Academy as the planner and coordinator of national scientific research. A detailed account of the role the Academy of Sciences, USSR, plays in the national electric energy R&D program was published in 1975 by the Academy.*

The energy program, according to this account, is being administered by the Department of Physicotechnical Energy Problems of the Academy of Sciences, USSR. M. A. Styrikovich, the department secretary, defined its principal area of interest as the complex of problems concerning national energy resources and their ecologic significance.

A. THE SCIENTIFIC COUNCIL ON THEORETICAL AND ELECTROPHYSICAL PROBLEMS OF ELECTRIC POWER

The Scientific Council on Theoretical and Electrophysical Problems of Electric Power appears to be the principal executive arm of the Department of Physicotechnical Energy Problems in the area of electric energy R&D. The council was established in 1968, with M. P. Kostenko, a

*Data on the organization of the Academy of Sciences are taken largely from [1].

member of the Academy of Sciences, as chairman. Figure 1 illustrates the organizational structure of the council.

The council maintains "working-level contact" with the State Committee for Science and Technology; this probably means that the two groups coordinate priorities for specific major R&D objectives. Such coordination is necessary in view of the official primary mandate of the council to focus on "the most urgent and promising" R&D work in the electric power area.

The council also has direct relations with over 40 research organizations whose parent institutions include the Academy of Sciences, VUZes, and industrial ministries. The council's degree of control over the R&D work of these organizations ranges from planning and coordinating the entire R&D activity, through assignment of individual projects, to permanent cooperation between the research organization and the council. Prestigious institutes that have for many years pursued such major research objectives as controlled fusion and MHD power generation are in the last category.

The R&D objectives within the purview of the council are divided among the six working sections, as shown in Fig. 1. Each section is concerned with the research of institutions falling into the specialized fields allocated to the section. The first four sections were established in 1969, one year after the council itself, to deal with the basic R&D subject areas of interest to the council.

Section 1: Design of advanced turbogenerators
Chairman: I. A. Glebov

Section 2: Generation and study of high electric and magnetic fields in power systems and the effects of these fields on man and the biosphere
Chairman: G. N. Petrov

Section 3: Study of nonlinear networks and design of the control components of power-generating systems
Former Chairman: L. P. Neyman (deceased)

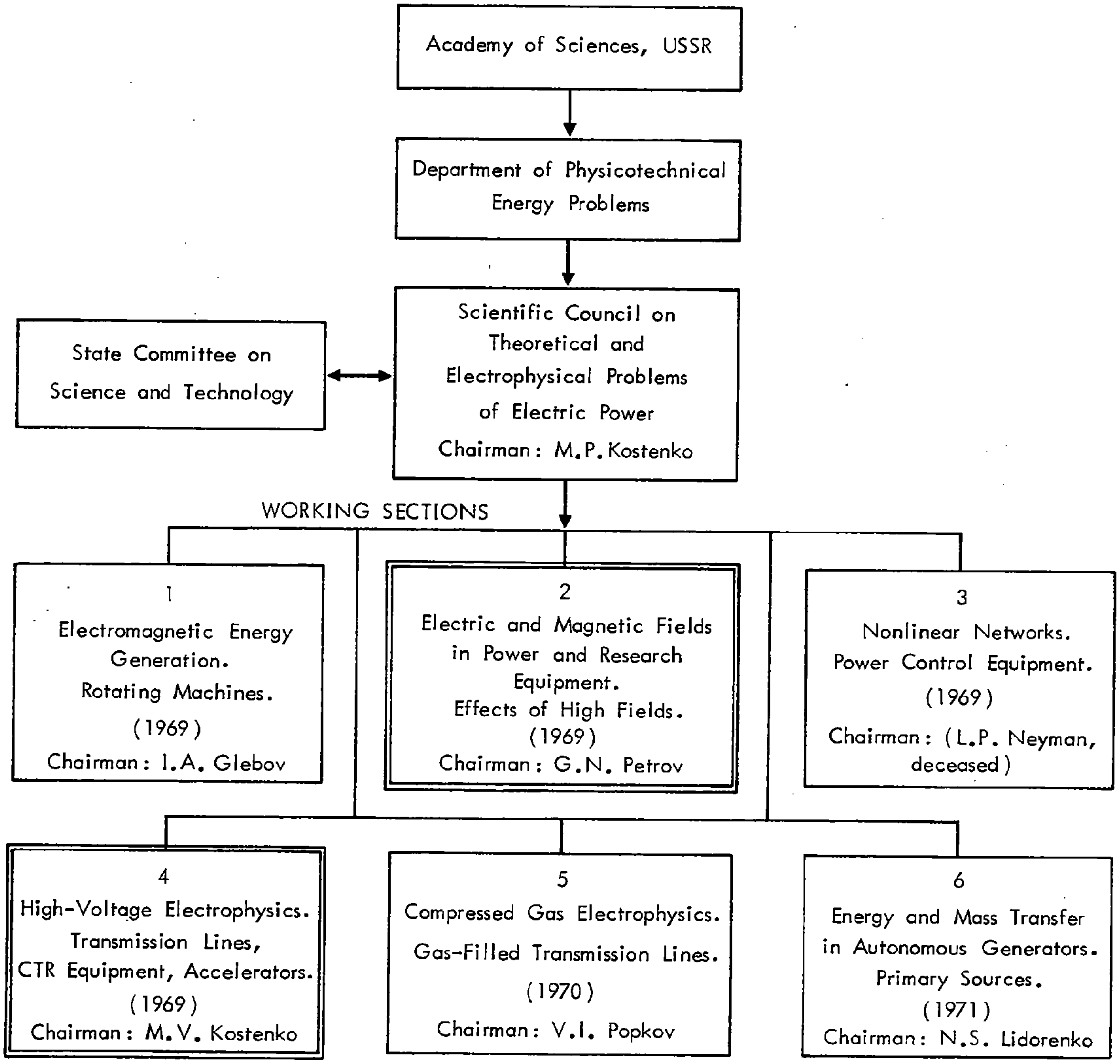

Fig. 1—Organization of electric power R&D in the Academy of Sciences, USSR

Sections 2 and 4 deal with pulsed power

Section 4: Design of specialized equipment with high performance parameters, including high-voltage transmission lines, high-current electron accelerators, switching systems, etc.

Chairman: M. V. Kostenko

Two additional sections were added later, Section 5 in 1970 and 6 in 1971.

Section 5: Use of gas-filled transmission lines as alternatives to conventional power lines

Chairman: V. I. Popkov

Section 6: Electric propulsion of transportation vehicles

Chairman: N. S. Lidorenko

Two distinct classes of R&D objectives emerge in the account of the council's subject areas of interest: The first class concerns electric-power generation and transmission for general use (in industry, for example); the second deals with electric-power systems developed for laboratory and advanced experimental applications. This distinction is also often reflected in the Soviet use of the terms "electric-power research" for the first and "electrophysical research" for the second. Clearly, pulsed-power R&D is of the latter type.

The two classes are discernible among the R&D objectives of each of the working sections of the council, particularly in sections 2 and 4, which cover electric and magnetic fields and devices designed, in Soviet terminology, for "extreme parameters." The two sections thus appear to be concerned to a considerable extent with pulsed power. Problems of extremely high fields dealt with in Section 2 are directly applicable to power-conditioning systems and charged-particle accelerators. In the formal account of the activity of Section 2, the extreme-parameter devices are defined as electromagnetic energy-storage systems, superconductive inductors, and generators of high pulsed fields. The stress on biological shielding against high fields evident in the program for Section 2 arises apparently from the large scope of applications of these devices.

The distinction between conventional and pulsed-power objectives is clearly manifest in the program of Section 4, which is responsible for (1) the design of advanced power-transmission lines and their protection from lightning and (2) the development of high-power energy-storage systems, and dielectrics subject to high voltage. Work on these two objectives does not seem to be evenly divided: The formal account of the plans and operations for Section 4 places the main emphasis on the pulsed-power aspects. The rationale for such an emphasis can be inferred from the following statement in the research plan of this section [1]:

> During the past 20 years, there has been a marked intensification of research in the USSR in the area of electrophysical processes; specifically, in the breakdown of liquid, solid, and combined dielectrics subject to various forms of applied voltage. . . . It should be emphasized that the study of the prebreakdown and breakdown phenomena in the micro- and nanosecond range, using the most advanced and sensitive electron-optical devices, and the analysis of electric strength of materials subject to short- and long-term action of voltage . . . were performed in the USSR ahead of world science.

The emphasis on pulsed power is illustrated in Fig. 2, which shows the recent missions and future objectives of Section 4. The two key missions in 1975 can be interpreted as conventional power transmission (Mission A) and pulsed-power design (Mission B). The objectives for the period 1975 to 1980, however, ignore the conventional power aspects and concentrate on topics that can be properly assigned only to Mission B.

B. CONTROLLED-FUSION RESEARCH

The emphasis on electrophysical processes is due largely to the pervasive interest in controlled-fusion research. In line with its mandate to concentrate on promising new electric-power research, the council in 1974 selected the engineering problems of thermonuclear energy conversion as the focus of its attention. The research

Section 4

HIGH-VOLTAGE ELECTROPHYSICS

Chairman: M. V. Kostenko

1975 Key Missions

A. Advanced Power-Transmission Lines

B. Design of "Extreme Parameter" Devices

Objectives for 1975-1980

1. Megavolt Nanosecond Generators
2. Capacitive and Inductive Energy Storage
3. Superstrong Magnetic Fields
4. High-Field Behavior of Metals and Dielectrics

Fig. 2--Present and future missions of Section 4, Scientific Council on Theoretical and Electrophysical Problems of Electric Power

organizations reporting to the council in this area are the Kurchatov Institute of Atomic Energy, the Institute of High Temperatures, and the Institute of Electromechanics. The council also appointed a commission of experts to report on the progress of research and to formulate a program of organization and coordination of the research work. The members of the commission of experts, drawn from the leading institutions in the field and the Academy of Sciences, are:

Ye. P. Velikhov, Kurchatov Atomic Energy Institute, Moscow

V. I. Popkov, Moscow

A. Ye. Sheyndlin, Director, Institute of High Temperatures, Moscow

I. A. Glebov, Director, Institute of Electromechanics, Leningrad

M. V. Kostenko, Academy of Sciences, USSR

K. S. Demirchyan, professor, Leningrad

V. S. Komel'kov, professor

V. A. Glukhikh, Yefremov Institute of Electrophysical Equipment, Leningrad

Velikhov and Sheyndlin are well-known leaders in the field of Soviet controlled fusion reactions. Demirchyan specializes in superconductive inductors. Glukhikh has done extensive work on inductive storage switching and also on homopolar generators. Glebov has considerable background in rotating power generators. The expert commission, therefore, has a strong pulsed-power background, which in the case of some members is not of the kind generally associated with either containment or inertial fusion reactions. This background is quite consistent, however, with the ostensible purpose of the commission of experts, that is, to study the engineering problems of converting the energy of pulsed thermonuclear reactors by means of plasma MHD generators.

The presence of M. V. Kostenko, Chairman of Section 4 (not to be confused with M. P. Kostenko, Chairman of the Scientific Council on Theoretical and Electrophysical Problems of Electric Power), on the commission of experts further reaffirms the strong pulsed-power role of Section 4 and of the council itself. It can be concluded, therefore, that Section 4 is expected to play a coordinating role in the organizational complex dealing with thermonuclear energy and involving the Academy of Sciences leadership, on the one hand, and the performing institutes, on the other.

The topical profile of Section 4, however, does not appear to correspond to the type of MHD engineering approaches favored by Velikhov and adopted by the council. Instead, Section 4 seems to be oriented more towards magnetic containment fusion and pellet fusion experiments initiated by lasers and electron beams. High-voltage nanosecond generators, particle accelerators, and high-density energy-storage systems are still at the stage of fusion research where ignition, rather than conversion and utilization, is the problem.

By the same token, Section 4 is also in a position to pursue and coordinate pulsed-power research in areas (other than controlled thermonuclear reactions) involving electron accelerators and high energy densities applied to a number of different technologies. One indication of such a possibility is the statement in the official account of the work of this section concerning the proposed research plans, in which "work on the problems of high magnetic and electric fields" is listed separately from "work on the engineering problems of utilizing thermonuclear energy" as timely topics requiring the attention of the Academy of Sciences.

C. R&D OBJECTIVES OF THE SCIENTIFIC COUNCIL

The account of the R&D planning of the Scientific Council on Theoretical and Electrophysical Problems of Electric Power includes an extensive listing of specific R&D target subjects for 1975-1980. The following items selected from that list illustrate the substantive plans of the scientific council in areas dealing with or related to pulsed-power R&D:

- Theoretical and electrophysical problems of designing megavolt nanosecond generators to drive high-power ignition devices
- Theoretical and electrophysical problems of designing capacitive and inductive energy storage systems for hot plasma experiments and for studies of industrial applications of such storage systems
- Design and study of superstrong magnetic fields for hot plasma containment
- Behavior of metals and dielectrics exposed to point action of extreme electric and magnetic fields
- Heat and mass transfer in energy converters with complex nonlinear parameters
- Transfer of charge and mass in liquids, gases, and solids in the presence of strong and magnetic electric fields to increase conversion efficiency
- Systems approach to the optimization of direct energy converters

- Study of cold plasma under inhomogeneous, nonequilibrium, and nonstationary conditions
- Study of cold plasma instabilities and turbulence
- Development of plasmatrons to heat hydrogen, nitrogen, air, methane, argon, helium, alkali metals, etc., to 3 K to 20,000 K and 100 atm; plasmatron electrodes for current density 1000 A/cm^2, energy input to pulsed plasmatrons of 10^8 J, power levels for 3-phase plasmatrons of 150 MW at 150 atm, and special power source for plasmatrons
- Electromechanical energy conversion: R&D of superconductive turbogenerators capable of operating at 2500 MW for thermal and atomic power plants
- Strong magnetic and electric fields in machines and transmission lines, including (1) the interaction of such fields with matter and (2) space charge in ionized media applicable to new technology
- Studies aimed at new ways of increasing voltage and field intensity, specifically in relation to the nanosecond pulse range
- Development of high-current pulse devices rated above 10^7 A, 10^7 V, 10^6 gauss
- Development of 10^{12}- to 10^{14}-W, 10^6-V, 10^{-9}-sec capacitive energy storage
- Development of switching systems for 10^8 A and 10^{-5} to 10^{-8} sec
- Development and study of inductive energy storage rated at over 10^8 J and the corresponding switching and power supply systems
- Development of rotating machinery systems with inertial mass storage of 10^9 to 10^{10} J to supply inductive storage and magnetic systems
- Development of supercritical plasma generators for 10^8 J
- Development of pulse power supply for ion-beam injectors rated at 100 A and 200 kV
- Development and study of megagauss fields

D. PERFORMERS OF PULSED-POWER R&D

The Scientific Council on Theoretical and Electrophysical Problems of Electric Power works on a permanent basis with 17 institutions, ranging from basic research institutes to manufacturing plants. An extensive analysis of Soviet technical literature showed nine of

these organizations, listed below, to be heavily engaged in pulsed-power R&D, thus verifying the fact that the Academy's plans in the area of pulsed-power R&D are indeed being implemented.

Kurchatov Institute of Atomic Energy, Moscow
Yefremov Institute of Electrophysical Equipment, Leningrad
The Elektrosila Plant, Leningrad
Institute of High Temperatures, Moscow
Leningrad Polytechnic Institute
Moscow Aviation Institute
Tomsk Polytechnic Institute
All-Union Research Institute of the Cable Industry
Institute of Electromechanics, Leningrad

The following emerged from the Soviet scientific literature analysis as the core institutes engaged in pulsed-power R&D; over one-half of these are also on the scientific council's list.

Leningrad
- Yefremov Institute of Electrophysical Equipment
- Leningrad Polytechnic Institute

Moscow
- Kurchatov Institute of Atomic Energy
- Institute of High Temperatures
- Institute of Mechanics, Moscow State University

Novosibirsk
- Nuclear Physics Institute
- Institute of Hydrodynamics
- Institute of Automation and Electrometry

Independent
- Tomsk Polytechnic Institute
- Tomsk Institute of Atmospheric Optics
- Moscow Aviation Institute

These institutes are considered the core performers for the purpose of this report, since they appear to carry out most of the significant work on pulsed power. Although other organizations also publish materials pertinent to pulsed power, their inclusion here would not contribute significantly to the overall picture.

The clustering of core institutes in the above list reflects not only the location of two or three of them in each of several cities, but also the fact that the institutes in each cluster work closely with each other. Intensive interinstitutional collaboration is an infrequent phenomenon in Soviet R&D. In the case of these institutes, the collaboration and joint publication of reports is so binding as to make it logical to consider each group--Leningrad, Moscow, and Novosibirsk--as a basic R&D unit. In addition, there are three institutes that work more or less independently of the others. These core institutes together deal with all the key topics of pulsed power, with some appearance of a division of labor among the groups.

The functional structure that emerges from an analysis of the core institutes is illustrated in Fig. 3. The key topics are more or less evenly distributed among the groups. The level of effort apparent in the treatment of each topic, however, differs from group to group. The thick bars designate a major effort in terms of published reports, the nature of the work, its continuity, and the number of scientists involved. The thin bars indicate a low level of effort in terms of the available publications. A note of caution: Despite the fact that "high" and "low" as applied to the level of effort are relative value judgments, the high-level designation, based on the definition given above, provides some assurance of a substantive activity actually under way in the given subject area. The low-level-of-effort designation, however, indicates only a relative paucity of relevant publications; it may not reflect the actual effort level.

The division of labor is evident in the major efforts. Electromagnetic flux compression and switching are the objectives of the Leningrad group; high-explosive flux compression, of the Novosibirsk group; MHD generators, of the Moscow group; homopolar and multipolar pulse generators, of the Moscow Aviation Institute and the Tomsk Polytechnic Institute, respectively. Superconductive storage is the only subject area in which two institutes (a Moscow group institute and the Moscow Aviation Institute) have major programs.

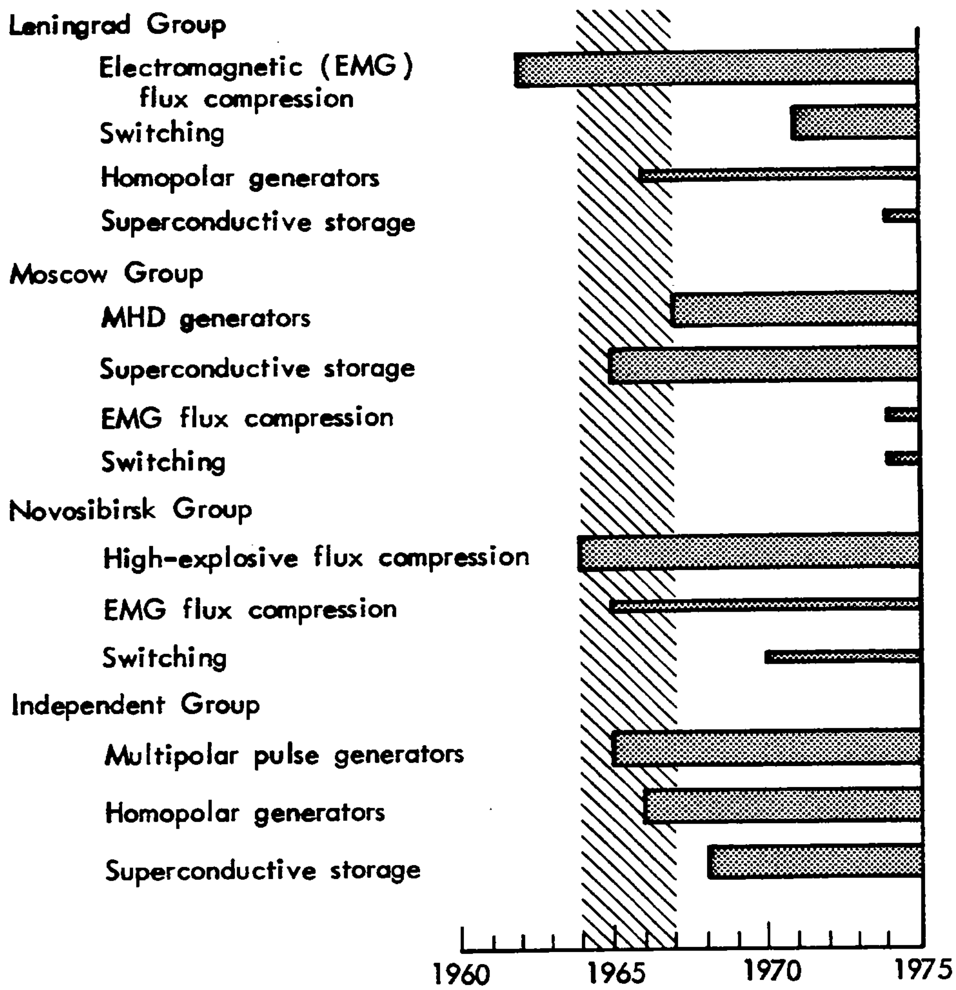

Fig. 3--Publication period and scope of major areas of pulsed-power R&D

The publication period indicated by the bars in Fig. 3 for each type of R&D is significant. The bulk of this work appears to have been started shortly before or during the three years from 1964 to 1967, since this is the period during which the research reports began to be published. It could be conjectured that these efforts have a longer history and that the period from 1964 to 1967 merely marks the declassification of the research reports. It is unlikely, however, that the publication of these reports resulted from the mass declassification of many diverse subjects within a relatively short time.

These publications lead to the assumption also that the number of scientific and engineering personnel engaged in pulsed-power R&D in the Soviet Union has been increasing at a fairly high rate. To test this assumption, we plotted the numbers of authors and papers of the core pulsed-power R&D groups over the years during which this work has been in evidence (Fig. 4). The significance of the resulting graph lies in the plotting method used. To approximate the total number of authors in all core institutes for each year, each author was counted for each year in which a paper by him was published, for each year between publications, for one year before his earliest publication, and for one year after his last publication, the assumption being that most likely he (1) remained active on the staff of the same institute between publications on the same subject and (2) did not join or leave the staff in the year of his first or last publication. These plotting rules thus remove the direct relationship between the number of authors and the number of papers for each year that results from simple counting of authors and papers.

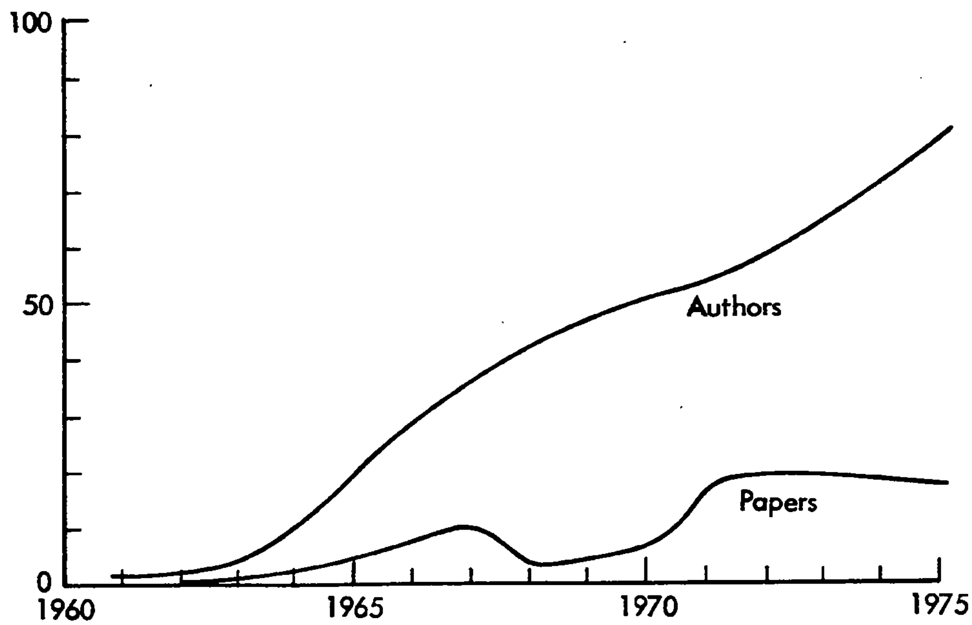

Fig. 4—Pulsed-power author and open-source publication trends in core institutes

The increasing divergence between the number of authors and the number of papers seen in Fig. 4 can be interpreted in only two ways: Either the number of papers being published was declining steadily over time, or the number of coauthors per paper was increasing. A check revealed that, insofar as the latter possibility was concerned, the number of coauthors per paper does not show any trends and has in fact dropped off somewhat in the past few years. Consequently, the first hypothesis must be true. In that case, however, the most plausible explanation must be a steadily increasing censorship of papers concerning pulsed power.

Figure 4 does not reflect the fact that 40 new authors affiliated with the Yefremov Institute began to publish in 1974. Some, if not most, of these must have been active at that institute for a much longer time. If these recent authors are added to the total, the actively publishing staff of the core institutes adds up to about 120 for 1975. A conservative estimate would place the number of authors who are members of other than the core Soviet research institutes working on pulsed power at one-half the number of core members, bringing the total of active authors on the subject of pulsed power close to 200. Past experience with research institutes engaged in some degree of design and construction of prototypes shows a ratio of 1 to 10 of authors to the total professional and technical staff. It is possible, therefore, that *the total manpower in the USSR currently engaged in the development of pulsed-power systems, as defined in this report, may well approach 2000 scientists, engineers, and technicians.*

III. ELECTROMAGNETIC COMPRESSION OF LINERS

This section discusses methods of producing megagauss magnetic fields by means of electromagnetic force; it is closely related to Section IV, which deals with the use of chemical high explosives for the same purpose. The explosively driven magnetic flux compression devices of the second method (the older of the two) made megagauss fields of large volume available in the laboratory for the first time. The simplicity of the high-explosive devices, however, and the high intensity of the fields they produced exacted a considerable price in terms of the special facilities required and the destruction of the associated equipment. The use of a capacitor discharge system to generate the electromagnetic force (the first method) avoids these disadvantages, but the resulting fields are less intense.

Fowler [2] recognizes two basic variants in the electromagnetic force method of producing high magnetic fields. The simpler variant requires only a load coil and a low-inductance capacitor bank as the energy source. In the second variant, a cylindrical conductor, the "liner," is inserted into the load coil. The liner, moving in radially, compresses the initial central magnetic field to much larger values. It is with this variant of the electromagnetic force method that much of the work on megagauss fields is concerned. The compression of magnetic flux by a liner can be used to obtain and confine thermonuclear plasma in megagauss magnetic fields. The liner serving as a power concentrator is accelerated to high speeds which, in principle, can impart superhigh densities to the plasma and produce energy outputs in excess of energy losses.

A discussion of Soviet theoretical research on the problem of magnetic flux compression, some aspects of which may also be pertinent to Section IV, and experimental research including that on the problem of thermonuclear plasma confined by imploding liners, follows.

A. SOVIET THEORETICAL RESEARCH

The principal research in the specialized area of magnetic flux compression by electromagnetic force appears to be conducted by a team in the Department of High-Voltage Engineering of the Leningrad Polytechnic Institute. The principal investigator is G. A. Shneyerson, Candidate of Technical Sciences; other key members of the team are V. T. Mikhkel'soo, A. B. Novgorodtsev, and A. P. Shcherbakov. The team conducts comprehensive research on flux compression by deforming conducting shells or liners, where the electromagnetic force, rather than chemical high explosives, produces the deformation. The team's publications have been appearing regularly since 1962. Early research was exclusively theoretical; the experimental phase commenced in the late sixties, with the results first published in 1970.

There are indications that Shneyerson's work originated in the attempts to develop new approaches to metalworking through the use of electromagnetic force and in research on induction heating. In connection with such applications, Shneyerson developed early methods of determining magnetic field configurations [3], generating high magnetic fields by capacitor bank discharges through solenoids [4], and heating of solenoids [5], all published between 1962 and 1964. Shneyerson thus came well equipped to the later study of magnetic flux compression for physics applications. It is possible that some of this later work was done in support of the R&D of theta-pinch and Z-pinch with imploding liner pursued by G. I. Budker and S. G. Alikhanov at the Nuclear Physics Institute in Novosibirsk.

A large proportion of Shneyerson's theoretical research was devoted to the problem of flux loss due to the penetration of an electromagnetic field into a conductor and the resulting heating of the conductor surface by eddy currents. These are essentially nonlinear effects which become important in magnetic fields of the order of 100 T (10^6 G). Approximate solutions were obtained for the depth of the skin layer and the current distribution in the layer for magnetic fields increasing exponentially, as a power of time, and discontinuously, for cases where $B > 100$ T [6]. In deriving these solutions, Shneyerson was concerned with a particular

configuration of the conductors, consisting of two massive blocks in series, separated by a plane gap. The gap was assumed to be infinitely thin and the blocks infinitely thick. The current oscillation in such a system was found to have a variable period caused by the changing effective inductance of the system as a result of the penetration of the electromagnetic field into the conductor [7]. An exact solution for the field in the conductor was obtained for the special case of a wave propagating at constant velocity. Such a solution was considered applicable even to nonlinear media, provided suitable boundary conditions were specified in the course of the analysis [8].

These considerations were applied to the case of a thin skin layer encountered in the production of superhigh pulsed magnetic fields in a limited volume. Since the frequency of the discharge current from a low-inductance capacitor bank was high, the depth of penetration of the field into the conductor was very shallow, making it possible to neglect the normal component of induction at the conductor surface. The massive conductor configuration used in the analysis consisted of a single-turn, rectangular-cross-section cylinder solenoid separated by a gap from a single-turn, plane solenoid. Approximate expressions, which took into account current leakage in the gap between the cylinder and the solenoid and leakage outside the gap, were then obtained for inductance [9,10].

Parallel with the development of Shneyerson's theory were his experiments involving the compression of liners. He obtained an exact solution for the compression of a cylinder in a high-magnetic field of a solenoid powered by an inductive store. Zero losses and instantaneous dumping of energy were assumed [11]. He also obtained an analytic expression for the efficiency η of deformation considered as a transient process in a system whose inductance was changed by an electromagnetic force capable of overcoming the mechanical resistance. The efficiency of deformation was thus a function of the storage system's capacitance C, initial voltage V_0, initial inductance L_0 and mass m of the element being deformed.

The efficiency was maximum when

$$q = \frac{\left(\frac{dL}{dx}CV_0\right)^2}{2mL_0} \approx 10 \qquad ,$$

where q is the field multiplier and x is the coordinate in the direction of deforming motion [12,13]. The efficiency of deformation is defined as the ratio of work spent on deformation to the energy stored in the capacitor bank [13].

A. M. Timonin of the Yefremov Institute demonstrated a limitation on this efficiency by obtaining

$$\eta = \eta_1\left(1 - \frac{q^2}{s}\right) \qquad ,$$

or the ratio of maximum field in the liner cavity, compressed to its minimum radius, to the compression field, where s is the liner compression ratio and η_1 is switching efficiency. The latter is defined as a function of the initial inductance of the storage system L_0 and the initial load inductance L_{20}, or

$$\eta_1 = \frac{L_0}{L_0 + L_{20}} \qquad .$$

This limitation on the energy conversion efficiency is significant for megagauss fields. Timonin claims that given s = 100, high energy conversion efficiencies are possible only for extremely high initial compression fields when $q \leq 7$ [14].

Shneyerson's experiments, involving thin (0.2 to 0.6 mm) and thick (1 to 2 mm) cylinders of aluminum, copper, brass, and duralumin, were designed to observe the conditions of stability of the cylinders during the implosion process. Shneyerson found that the simple inertial motion theory, as used by Alikhanov, is valid only for cases of fast deformation [15].

Two types of 100-mm-long single-turn solenoids were used: one, 75 mm, the other, 100 mm in diameter. A 14:1 pulse transformer

discharged a 92-kJ, 12.8-μF capacitor bank across each solenoid. The error in the measurement of liner radius did not exceed 0.7 mm. The reproducibility of the results was very good. The maximum velocity of deformation V_m was within the limits of 100 to 900 m/sec. The efficiency η was calculated from the experimental data with an accuracy of 20 percent, according to the formula,

$$\eta = \frac{mV_m^2}{CV_0^2} \quad .$$

The efficiency here is interpreted as the ratio of the kinetic energy of the moving liner to the energy stored in the capacitor bank. The maximum η of 18 percent was comparable to Alikhanov's [16] and Cnare's [17] results. The experimental values of η were always lower than the theoretical values, however, even in the case of very light liners. The discrepancy is attributed to the idealized, purely inertial model of the moving liner, as well as to such obvious factors as heating losses. The theoretical results, based on the assumption of a purely inertial motion, were in closer agreement with experimental data only for $V_m > 500$ m/sec. The instability of the liner was treated merely in terms of its characteristic length λ, and no significant findings were reported beyond the observation that λ is a function of the degree of radius compression [8].

In a more recent series of experiments with the same capacitor bank, Shneyerson obtained a field of over 300 T under conditions providing for symmetric compression. The results were in agreement with theory, which took into account liner and solenoid skin effect and compressibility of the liner material. There was no initial externally applied field; the flux penetrating the liner was captured, giving rise to the axial magnetic field.

Shneyerson, in more than 50 experiments, used solenoids with radii varying from 35 to 100 mm and Cu, Al, and brass liners about 0.5 mm thick. The necessary symmetry was enhanced by a special foil shield, the use of narrow-slot solenoids, and uniform liner thickness [18]. The Leningrad Polytechnic Institute developed

a fast magnetic camera shutter with a 60-mm aperture and speed of 200 μsec to be used in Schneyerson's experiments. Similar shutters reported previously in the literature had aperture diameters of 25 mm [19].

Capacitor discharge across a solenoid is the basic phenomenon underlying the concept of generating megagauss fields. The fundamental relationships governing such a discharge continue to be the subject of theoretical and experimental investigation by such leading research facilities as the Nuclear Physics Institute in Novosibirsk and the Kurchatov Atomic Energy Institute in Moscow. V. I. Yurchenko of the Nuclear Physics Institute analyzed the theoretical skin effect in massive conductors in 1973-1974. The single-turn solenoid for megagauss fields is considered too complex a structure to which to apply an exact analytical solution for determining the skin effect. Yurchenko therefore applied the solution to simpler structures approximating the solenoid [20]. In one case, in which he used two parallel rails of infinite thickness, he found that the Shneyerson efficiency decreased as the thickness of the skin layer increased. Subsequently, Yurchenko extended the exact formulation of the flux loss problem to structures other than parallel rails, alleging that this was the first time that such an experiment had been described in the published literature [21]. Based on the constraints given for the thickness of the skin layer, Yurchenko arrived at the optimal configuration of structures undergoing flux compression from the viewpoint of flux loss. The optimal configuration was defined as one whose contour length decreases upon compression.

A. I. Pavlovskiy, in 1974, performed simple experiments with capacitor discharges into a solenoid, on the assumption that skin effect in a cylindrical conductor can be evaluated only qualitatively [22]. The experiments were carried out with a 3-mF, 1.35-MJ MKB-1 capacitor bank discharging into a massive trapezoidal single-turn copper solenoid (1 cm in internal diameter, 1 cm long, 6 cm in external diameter, 0.15 cm gap, 44 nH inductance). Residual

deformation corresponding to the limit of the elasticity of the copper appeared above 0.4 MG. For an initial capacitor voltage of 30 kV, the discharge current reached a peak of 6 MA; the peak field produced in the solenoid was 1.9 MG.

After the discharge, the solenoid diameter increased to 5 cm, and 30 percent of the copper by weight was lost through axial ejection. These effects, as well as field diffusion, reduced the peak magnetic field from the theoretical value of 3 MG. The current-carrying skin layer was found to explode at 1.7 MG. To evaluate this effect, if only qualitatively, Pavlovskiy replaced the solenoid with a cylinder (0.4 and 0.8 cm in diameter, 2 cm long) and made an approximate numerical computation of the field diffusion. He found that the skin layer at first heats up quickly, decreasing conductivity, and at the same time, both the magnetic field and current diffuse into the metal. After a time, the relaxation of the magnetic flux produces a reverse diffusion of the field and a change in sign of the electric field on the surface. The change causes a reverse current in the skin layer and a ponderomotive pressure directed away from the metal. The pressure produces an explosion of the surface.

Pavlovskiy concluded that he could increase the peak magnetic field by shortening the characteristic time of the discharge and by using for the solenoid a material that is less plastic than copper.

B. THETA- AND Z-PINCH WITH CONDUCTING LINER

Early pinch experiments with conducting liners were performed at the SP facility of the Nuclear Physics Institute, Novosibirsk, by S. G. Alikhanov, G. N. Kichigin, and others, under G. I. Budker's initiative and guidance. The publications describing these experiments are dated 1966 and 1967. The explicit goals of this work included controlled thermonuclear reactions, high-energy physics, and solid-state physics. Budker used the term "magnetodynamic cumulation" to designate the effect of magnetic pressure accelerating the liner. This method is considered preferable to the high-explosive system because it is less expensive in long experimental series and

permits indoor work. In all of the SP facility's experiments discussed below, the power supply was provided by a 700-KJ capacitor bank consisting of 384 units [23].

Experiments with the theta-pinch of metal liners yielded liner energies of 100 KJ. This magnitude, representing the kinetic energy of the imploding liner and amounting to about 25 percent of the energy stored in the capacitor bank, corresponds to Shneyerson's efficiency η and, as noted above, is comparable to Shneyerson's results [16]. Alikhanov found that the external magnetic field did not cause macroscopic instabilities in an aluminum liner (80-mm external diameter, 2.5-mm wall thickness, 150-mm length, 250-g mass). The liner maintained its initial cylindrical form throughout the implosion process. Field magnification exceeded 100. The 100 KJ of kinetic energy exceeded the results previously obtained by Cnare [17]. The magnetic field accelerating the liner was established by a massive 400-kg single-turn steel solenoid 150 mm long and 120 mm in internal diameter. The solenoid withstood 1000 shots with currents reaching 3 MA without deformation [23].

The Z-pinch converts more energy of the capacitor bank into kinetic energy of the liner than does the theta-pinch and therefore produces higher magnetic fields. The Budker group's Z-pinch experiments produced magnetic fields of up to 3 MG and currents of up to 5 MA. During the implosion in the Z-pinch configuration, as with the theta-pinch, the liner maintained a correct cylindrical form, considered the main prerequisite to the generation of high magnetic fields [24].

The open-pinch-with-liner-systems designed for very high performance parameters are intended primarily to achieve controlled fusion reactions. A small team at the Kurchatov Institute of Atomic Energy in Moscow, consisting of Ye. A. Azizov, V. V. Breyev, Ye. A. Zotova, and I. A. Ivanov, recently evaluated the suitability of the theta-pinch with liner system as a means of reaching the break-even point in the development of controlled fusion. Their evaluation was based on the theoretical findings of Shneyerson, discussed above, and his efficiency (η) concept. They claim, however, that Shneyerson's

analytical solution of the current density distribution in the liner is open to some doubt. Specifically, Shneyerson's expression for the external field discontinuity is not accurate near the conductor's surface, precisely the region in which the electric potential must be known in order to determine the rate of flux loss. The Kurchatov team's analysis of this problem has led to prohibitively high requirements for the break-even parameters of 2×10^9 J of stored energy and 3×10^{14} W of discharge power. Their conclusion, thus, was that the development of open-pinch-with-liner systems capable of reaching the break-even point would require at least 10 more years [25].

The development of theta-pinch-with-liner devices is, nevertheless, continuing in the Soviet Union. The major R&D center at this time is the Yefremov Institute in Leningrad, where this work is represented by Project DVIN [26,27,28]. The key participants are V. A. Zheltov, A. S. Kibardin, A. V. Ivlev, A. M. Timonin, and Yu. A. Morozov. The DVIN team was joined by V. G. Kuchinskiy of the Leningrad Polytechnic Institute and by A. V. Komin of the Institute of Nuclear Physics in Novosibirsk. All told, the project has 19 active authors.

Project DVIN's first stage of development appears to have been completed with the construction and testing of a prototype model of inductive storage for 1.5 MJ and 15 GW. The model features the multiplication of the pumping current in the form of three-stage mechanical series-to-parallel switching of the solenoid turns. There are four turns in a single layer, 2 m in internal diameter and 0.25 m long. The solenoid is supplied with power by a homopolar generator with 4 MJ stored in the rotor at 90 V.

The second stage of Project DVIN is a larger system designed for 20 MJ and 200 GW. The solenoid is 1.6 m in internal diameter and 2 m long, with 160 turns, each turn being designed for 50 kA. A three-stage switching system dumps the energy in 10^{-4} sec. The power supply can provide a maximum voltage of 100 to 200 kV, with a peak current of 8 to 40 MA at the load [26].

Despite its own pessimistic prediction on the near-term realizability of high-performance open-pinch devices, the Kurchatov Institute

is continuing research with three such systems. According to L. I. Rudakov, the objective of the research is "the search for optimum variants . . . using metal liners accelerated by magnetic pressure" to compress plasma. The first system is a superfast pinch with a liner, called the LN-20, driven by a capacitive storage of 2 MJ. Compression coefficients of not less than 50 have been obtained with aluminum liners.

The second system is a belt-pinch with liner, featuring an elongated toroidal magnetic structure, which R. Kh. Kurtmullayev, who is in charge of the research, hopes will require only 10 MJ for a thermonuclear demonstration experiment. Kurtmullayev and his team showed that an initially cylindrical metal liner could achieve three-dimensional motion to form a toroid. A megagauss toroidal field with a magnification of 25 to 30 and a field growth rate of 3×10^{11} G/sec was demonstrated experimentally by such a configuration. The three-dimensional compression coefficient was 10^3, maximum gas pressure reached 10^5 atm, and the total efficiency was 3.5 percent. A stronger liner wall and higher accelerating field intensity were expected to boost the total efficiency to 30 percent and gas pressure to 10^6 atm. To obtain the three-dimensional cumulating liner, the wall of the liner cylinder was made thicker toward the center of the cylinder, resulting in a faster motion and earlier closure of the ends of the cylinder. Kurtmullayev considered the sharp peaking of power developed by the imploding liner to be a special feature rendering this device particularly suitable for use as a magneto-cumulative generator of high-current pulses [29].

The third system is involved in an experiment with plasma compression by a liner, using two pulsed plasma injectors and a fast TIN-1 inductive storage. The latter, capable of storing 20 MJ, has a theoretical maximum discharge power of 100 GW. These specifications place the TIN-1 in the same category as the second-stage DVIN. The total efficiency of converting the energy stored in the TIN-1 to plasma energy inside the imploded liner is 20 percent, so that the energy content of the liner is expected to reach 4 MJ [30].

IV. MAGNETIC FLUX COMPRESSION GENERATORS POWERED BY CHEMICAL EXPLOSIVES

The use of explosive flux compression to obtain megagauss magnetic fields, the subject of considerable research in the United States, the Soviet Union, and elsewhere, is discussed below in terms of recent Soviet developments as applied to pulsed-power technology.

A. D. Sakharov and his group at the Kurchatov Institute of Atomic Energy in Moscow initiated the research and development of explosive flux-compression devices based on the use of chemical explosives in the Soviet Union. Since the mid-sixties, however, most of the work in this field appears to have been done by Ye. I. Bichenkov of the Institute of Hydrodynamics in Novosibirsk, largely at the initiative of and under the guidance of G. I. Budker, the leading developer of charged-particle-beam accelerators, of the same institute. The connection with Budker indicates that one of the primary goals of Bichenkov's research is the application of chemically powered explosive flux compression devices to high-current charged-particle accelerators. The significance of Bichenkov's work is underscored also by the attention given it by Academician M. A. Lavernt'yev. A. Ye. Voytenko of the Institute of Nuclear Physics in Novosibirsk provides technical support to Bichenkov; other key members of the group are A. F. Demchuk, B. I. Kulikov, V. A. Lobanov, and Ye. P. Matochkin.

Bichenkov is vague in defining the purpose or objectives of his research, confining himself to statements to the effect that explosive magnetic generators are a promising tool for experimental work in the area of high-temperature plasma and pulsed megagauss electron accelerators. He has also said, somewhat more specifically, that the application of megagauss magnetic fields obtained by explosive techniques to accelerator technology reduces accelerator dimensions to a minimum. The main advantage of explosive magnetic generators over capacitor banks in powering high-current sources, according to Bichenkov, is

the higher output power and energy. These generators are also more economical at energy levels in excess of 1 MJ. Of the several different possible configurations of the explosive flux-compression devices--bellows, coaxial, and helical--Bichenkov appears to prefer the plane-type, or bellows generator. Bellows are simpler to build than coaxial generators, permit easy control of the pulse shape by controlling the rail profile, and are convenient for staging several units in series or parallel configurations.

Bichenkov's R&D work led Voytenko to state in 1973 that the operating principles of explosive magnetic generators were understood sufficiently well to commence their practical application. The published example of such an application was a modest one involving a small generator powering a plasma discharge. An interesting aspect of this effort was that it also represented a practical example of the detonation of an explosive device inside a laboratory, an operation made possible by a protective detonation chamber specially designed and built for Bichenkov's work.

The approach evident in this project stresses systematic theoretical analysis of the basic problems specific to chemical-to-magnetic energy conversion, particularly the analysis of the diffusion losses of the magnetic flux. The concurrent experimental work, as reported in the available sources, served mainly to verify the theoretical findings and to enhance the understanding of the process rather than to achieve record performance. For this reason, none of the known experimental results appears to have exceeded the magnetic field and current values achieved in Sakharov's original experience.

The project seems to have been well under way in 1964, when the early theoretical work was published. The next series of reports appeared in 1967-1968, followed by the most recent experimental series in 1973-1975. For the sake of clarity, the following detailed technical account has been divided into two parts, the first tracing the progress of the theoretical argument and the associated verification experiments and the second describing the independent experimental activity.

A. THEORY OF FLUX COMPRESSION AND FLUX LOSS

The effect of finite conductivity is evaluated for the case of field compression by two infinite plane conductors approaching each other at constant speed. Assumed are constant conductivity and homogeneous magnetic field. The objectives of the evaluation are the limiting magnetic field and the effective skin depth. It is assumed that at low compression speeds the limiting magnetic field is proportional to $\sqrt{v_0\sigma}$ (v_0 is the conductor velocity) and that the entire magnetic flux leaks into the conductor. At high compression speeds, it turns out that the limiting magnetic field is proportional to $v_0\sigma$. The depth of the skin layer is inversely proportional to the limiting magnetic field. As long as the depth of the skin layer is much smaller than the gap width, the compression process resembles the case of zero resistivity. If the skin layer exceeds the gap width, the effect of finite conductivity becomes decisive. It follows, therefore, that at constant compression speed, the entire flux leaks into the conductor at the end of compression, when the gap width tends toward zero. The limiting field is a function of the conductor position [31].

Using an extremely simple approach, Bichenkov subsequently gave a more general treatment of flux conservation in the cavity and in the conductor for any kind of motion of the conductor. A special case was considered when the conductor velocity was such as to keep a cylindrical cavity flux constant even if conductivity was finite. For zero flux leakage from the cavity, the field in the cavity must be proportional to $1/r^2$ and the field in the conductor to $1/r\delta$, where r is the radius of the cavity and δ is the depth of the skin layer. It follows that constant flux distribution between the cavity and the conductor demands that $r \sim \delta$, i.e., that the radius of the cavity must increase over time t at the same rate as the skin layer depth. For $r \sim \sqrt{t}$, the skin layer also will be found to increase as $\sqrt{t}$. For an incompressible conducting fluid, the condition $r \sim \sqrt{t}$ corresponds to the case of a single source or sink of constant intensity q. If the sink lies at infinity, i.e., the cavity is expanding, then the required conductor velocity must be

$$v = \frac{q}{2\pi r}$$

for the flux in the cavity and in the conductor to remain constant. Under this condition, the flux in the cavity will differ from the initial flux by the magnitude $1/\sqrt{(1/2)R_m}$ at high velocities and by $\frac{1}{2}\, R_m^{1+(1/2)R_m}$ at low velocities [32]. Here R_m is the magnetic Reynolds number.

The concept of the simple dependence of velocity on radius, $v = q/2\pi r$, is further considered in Bichenkov's more recent paper, in which he gives self-similar axially symmetric solutions assuming constant conductivity. In the case of the expanding cavity, the flux distribution between the cavity and the conductor remains constant; in the case of a collapsing cavity, the entire flux leaks into the conductor, even though the field in the cavity increases without limit. This means that flux leakage cannot impose a limit on the magnitude of the field obtained by compressing flux in a cylindrical cavity. For large Reynolds numbers, the flux in the collapsing cavity decreases slowly at first and quickly drops to zero at the end of compression [33].

The preceding theoretical findings of the principles of flux diffusion into moving conductors were subsequently applied to the design of a model of a flux-compression generator. The bellows type was chosen because of the simplicity of design and good energy characteristics. The model assumes a homogeneous magnetic field in the cavity, zero sliding contact loss, constant-width, infinitely thick rails, and infinite conductivity of the piston and shorting bar. Magnetic flux can escape only in the direction perpendicular to the surface of the side rails, assumed to have constant conductivity.

The current source "pumping" the generator sets up the initial magnetic field. The initial distribution of the magnetic field $B_0(x)$ in the conducting walls depends on pumping time t_0 and on the pulse shape of the pumping current. However, magnetic flux diffusion losses were found to depend weakly on the pumping current pulse shape and mainly on t_0 and R_m.

Two extreme cases of pump behavior were distinguished: slow pumping ($t_0 \to \infty$), in which the field penetrates deeply into the wall, and fast pumping ($t_0 \to 0$), in which the field does not penetrate into the wall, so that $B_0(x) = 0$ and $B_0(0) = 1$. Flux diffusion losses F* are evaluated for the fast and slow pumping regimes within a range of magnetic Reynolds numbers from 1 to 80. For $R_m \gg 1$, the ratio of flux losses in fast and slow pumping regimes is found to be

$$\frac{F^*_{fast}}{F^*_{slow}} = \frac{3}{2} \quad .$$

Fast pumping thus causes larger loss, which is considerable even for high Reynolds numbers; for example:

$$\text{for } R_m = 50, \; 23\% \leq F^* \leq 45\%$$

and

$$\text{for } R'_m = 10, \; 56\% \leq F^* \leq 72\% \qquad [34].$$

The sequence of theoretical research on flux diffusion into conductors was recently followed by verification experiments. The diffusion loss was found to be excessive above a critical current line density of 180 to 210 kA/cm; the excessive loss was attributed to a hypothetical flute instability in copper conductors.

Figure 5 represents the experimental explosive flux-compression generator described in [34]. The rails were made either of copper or duralumin. The HE cartridge was filled with TG 50/50 cast explosive. A 10-mF, 4-kV capacitor bank was discharged across the rails. The explosive was detonated at the point of peak current. The current was measured by means of inductive pickup coils in the plexiglas slab. Experiments were performed for different initial currents I_0 and different distances D between the rails and the cartridge. For copper rails, distance D varied from 3 to 20 mm and I_0 from 240 kA to 410 kA. For duralumin rails, D varied from 5 to 20 mm and I_0 from 100 to 400 kA. The pumping current was assumed to vary as $\sqrt{t/t_0}$, where t_0 is the pumping time. Measurements of the maximum current for

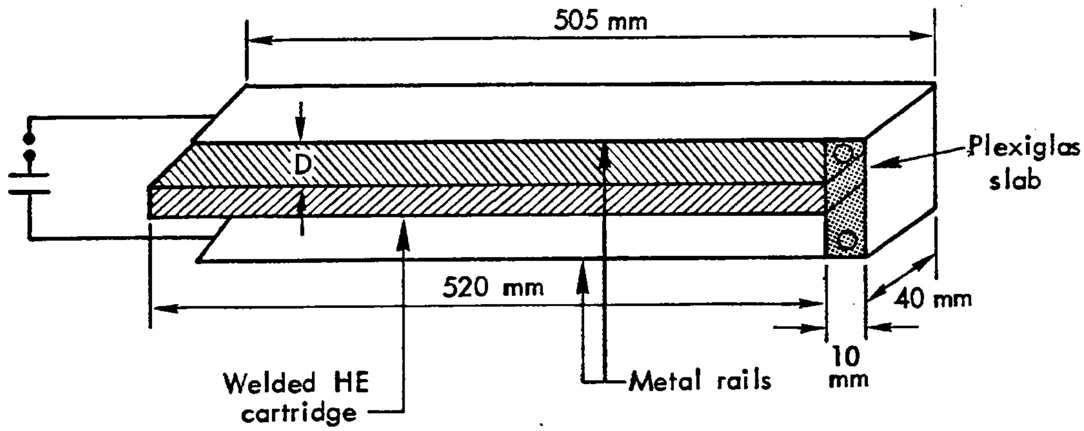

Fig. 5--Plane flux-compression generator

the copper rails revealed rather weak dependence on D: for D = 3 mm, I_{max} = 2.4 MA; for D = 5 mm, I_{max} = 2.6 MA; and for D = 10 mm, I_{max} = 2.7 MA [35].

The calculated Reynolds number varied from 3 to 80. For small D (narrow gaps) and low initial currents, the experimental data were found to be in agreement with flux loss calculations according to Bichenkov's theory [34]. For large D (wide gaps) and low initial currents, however, the experimentally determined flux loss corresponded to the theoretical values only in the beginning of compression. As the initial current increased, losses at the end of compression exceeded diffusion losses in all experiments, especially in the case of D = 20 mm. For copper rails, flux loss was strongly dependent on the initial current. Above a critical value I* of I_0, flux loss sharply increased. In all experiments with copper, I* was the same within experimental accuracy: 760 to 840 kA corresponding to the magnetic field in the cavity of 230 to 250 kG.

Duralumin conductors did not reveal the presence of any significant critical current, with the exception of the 20-mm gap, which provided a hint of excessive loss above 1.3 MA (400 kG). Inasmuch as the pressure of a 250-kG field on the conductor amounts to 2.5 kbar, which is beyond the limit strength of copper, some flute instability due to bending can be assumed. In the contact between rippled surfaces, the flux trapped within the ripples is lost for further compression. Correction for this loss computed on the basis of MHD considerations brought the experimental results into agreement with theory [35].

There appears to be little contributory theoretical work in the USSR on the problem of magnetic flux compression by chemical explosives outside Bichenkov's team. The only known exceptions are papers by N. N. Kalitkin and L. S. Tsareva [36] and by I. M. Rutkevich [37], all of Moscow. Kalitkin and Tsareva of the Institute of Applied Mathematics provide an approximate theoretical method of calculating the magnification of the magnetic field by solving a few ordinary differential equations. In a few cases, they were able to obtain exact solutions. Rutkevich derived analytical expressions for the plane and coaxial generators in an idealized case of infinite conductivity.

B. DESIGN AND TESTING OF FLUX COMPRESSION DEVICES

Bichenkov has been involved in comprehensive experimental work with all three basic types of explosive-driven flux compression devices--bellows, coaxial, and helical [38]. The guiding principles of this work were as follows. The peak magnetic field was selected from the viewpoint of the mechanical strength of the generator, considering the skin layer heating, metal ejection, and loss of conductivity. The operating period of the cycle was limited on top by the decay time of the magnetic flux and on the bottom by the allowable stress, energy, and load inductance. The diagnostics employed for input current measurements held the scatter among independent readings to within 15 percent. The general experimental

data obtained for the three types of explosive flux compression devices are given as follows:

	Generator		
	Bellows	Coaxial	Helical
Generator			
Initial inductance	180 nH	110 nH	1.9 μH
Load inductance	7 nH	14 nH	50 nH
Initial current	$(90-95)\times10^3$ A	$(2-8.2)\times10^5$ A	10^5 A
Final current	$(1.6-2)\times10^6$ A	6.5×10^6 A	2×10^6 A
Current multiplication ratio	20	8	20
Magnetic field energy to load	--	$(2.8-3)\times10^5$ J	--
System efficiency	--	14%	--

The Bellows Generator

Bichenkov's bellows generator (Figs. 6 and 7) consisted of two 1.5-mm copper strips. The high-explosive bar was 10 mm thick at the capacitor end and decreased to 5 mm at the coil end. The two strips were separated by a wide insulated sheet of copper (not shown). The operation of the generator at the above initial current was found to be stable. An increase in the initial current by a factor of 2 or 3 disrupted the operation.

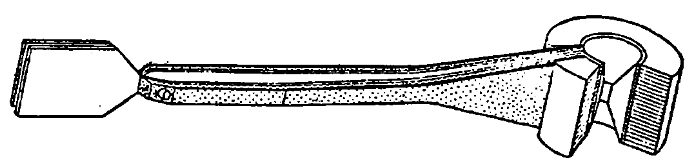

Fig. 6--Bellows generator, general view [38]

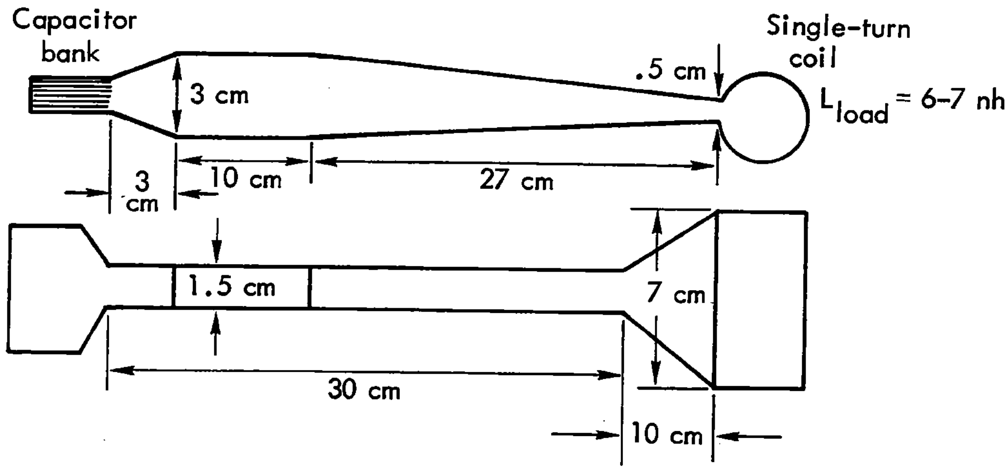

Fig. 7--Bellows generator, dimensions [38]

The Coaxial Generator

The coaxial 2.5-mm copper tubes were force-fit into a steel cup (Figs. 8 and 9). The section of the tubes inside the cup represented the load. The high-explosive charge, which had a total weight of 380 g, equivalent to (1.9 to 2) x 10^6 J, was split inside the inner tube into four longitudinal segments to prevent transverse breaks.

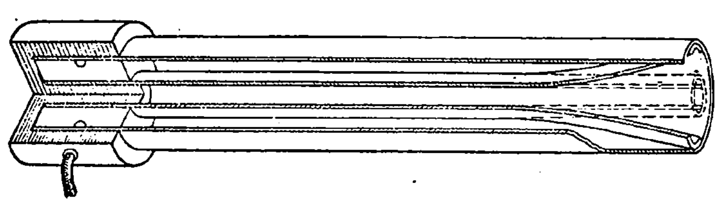

Fig. 8--Coaxial generator, general view [38]

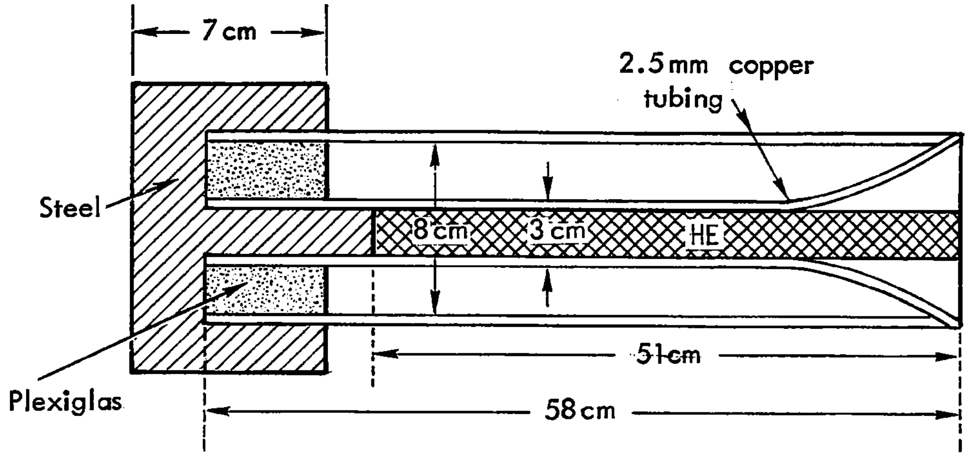

Fig. 9--Coaxial generator, dimensions

The time behavior of the ratio

$$\frac{dI}{dt} I^{-2}$$

indicates flux conservation in the operation of a coaxial generator. This ratio is constant in an ideal generator operating at a constant flux compression rate and constant inductance at each point. The ratio, found to be constant also at low initial currents, decreased somewhat near the upper end of the initial current range. The generator operation was stable for the following dimensions of the tubes:

Internal diameter of outer tube	80 mm
Internal diameter of inner tube	30 mm
Length of tubes	58 cm
Length of HE charge	51 cm

When the tube diameters were reduced by a factor of 3 for the same length, to increase the field, the operation was unstable. The operating parameters in this case were:

Initial current	6×10^5 A
Final current	$(3.7 \text{ to } 4.2) \times 10^6$ A
Final field	$(1.5 \text{ to } 1.7) \times 10^6$ Oe

The Helical Generator

The high-explosive charge and blanket were placed outside the conductors. Considerable difficulty was encountered in building a simple solenoid capable of withstanding 10^5 G for 100 μsec. With a dense winding of 1 turn per cm, it was possible to achieve a current multiplication ratio of 20. Flux loss, ranging from 1/2 to 2/3 of the initial flux, depended strongly on the accuracy of the component alignment. A better performance was obtained from less dense windings (1 turn per 3 to 4 cm) inside a compressing shield, yielding a flux loss of 1/3. However, the system efficiency in this case did not exceed 2 percent. A system efficiency of 10 percent was obtained from a two-stage scheme using two small coaxial generators connected by a transformer (n = 3) [38].

Detonation Chamber Experiments

Following the 1967 experiments, Bichenkov appears to have concentrated on the bellows generator [39]. He was able to perform a new series of experiments inside the laboratory, thanks to the new detonation chamber designed specially for this purpose by Voytenko [40]. The experiments were performed jointly by the institutes of Hydrodynamics and Nuclear Physics in Novosibirsk, again under the sponsorship of G. I. Budker. A bellows generator with an inductive and resistive load was used in these experiments (see Fig. 10).

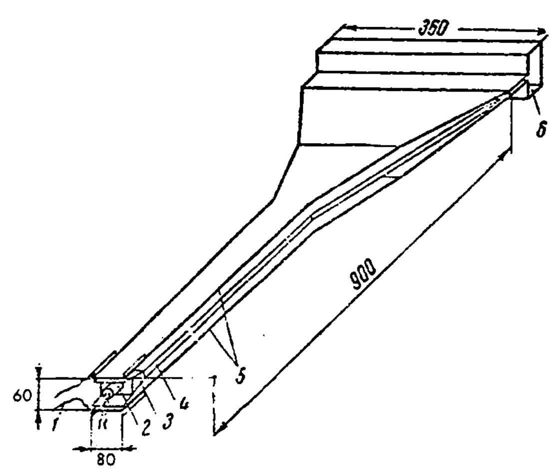

Fig. 10--Bellows generator used in detonation chamber experiments (dimensions are in mm) [39]

The initial current of 0.5 MA was supplied from a 100-kJ capacitor bank to copper rails 5. High explosive 3 filled copper cartridge 4. The detonation wave traveling along the high explosive caused the cartridge casing to move at 2 km/sec, closing the circuit of the copper rails and trapping the magnetic flux. The 2-mm rail thickness assured a minimum of distortion from the magnetic force.

The following experimental results were obtained [39]:

Output current	14 MA
Output energy	1 MJ
Peak power	5×10^{11} W
Weight of HE	1 kg
Total weight	10 kg
HE utilization efficiency	15%

These experimental results were considered analytically for the general case of the bellows generator (shown in Fig. 10, p. 37), connected to various types of loads with resistance and inductance: (1) constant resistance; (2) resistance increasing linearly with temperature; and (3) plasma load with equilibrium emission, connected across a matching transformer [41].

<u>(1) The Case of Constant Load Resistance</u>. The variation of the rail profile depends on the value of the constant load resistance R_0. If $R_0 \to 0$, the rail profile is exponential. There is a critical value R_* of R_0 for which the rail width and generator current are constant. For $R_0 < R_*$, the rail width and generator current increase; for $R_0 > R_*$, they decrease. The latter case entails a considerable loss of magnetic flux and is considered undesirable in many respects. The maximum energy delivered to the load coil is a function of $\rho = R_0/R_*$, which is in turn related to $n = L_0/L_1$, where L_0 is the initial inductance of the generator circuit and L_1 is the load inductance.

Thus, the maximum energy E delivered to the load in terms of initial energy E_0 of the magnetic field in the generator, for a given n, is $E/E_0 = (n + 1)^2/4n$ and is reached when $\rho = n + 1/(n - 1)^2$. The current multiplication in this case is $(n - 1)/2$.

For $\rho = 1$ and constant current, $E = 2E_0[1 - (1/n)]$ and is approximately double the initial energy in the generator.

For the most interesting case of $n \gg 1$,

$$E = E_0\rho\frac{(1 + \rho)n^2}{(1 + \rho n)^2}$$

and the maximum energy is reached for

$$R_0 = n^{-1} R_* \quad .$$

Under this condition, one-half of the energy developed by the generator is converted into heat and the other half remains as the energy of the magnetic field due to the residual inductance of the generator.

(2) The Case of Variable Load Resistance. For a fixed n and load resistance increasing with time, more energy will be developed than in the case of fixed resistance. Generators with variable rail width show greater system efficiency than those with constant rail width. Efficient heating of the high-resistance load requires a matching transformer between the generator and the load.

(3) The Case of a Plasma Load Whose Resistance Decreases with Increasing Temperature:

$$R = R_0 \left(\frac{T_0}{T}\right)^{3/2} \quad .$$

For large coefficients of transformation m, the load current is low; the plasma is strongly cooled by radiation and its resistance at first increases. In such a case, the energy contribution from the high explosive is significant only at high powers, or fast operation, of the generator. Inasmuch as the energy losses of dense plasma depend largely on temperature ($\sim T^4$), the plasma's resistance will change by a factor of only 2 to 2.5. The highest energy is delivered to the load by proper matching via a suitable transformer. Low m causes an increase in the effective load resistance and rapid relaxation of the magnetic flux. In the given case, the optimum was m = 4 [41].

An operational bellows generator (Fig. 11) was built at the Nuclear Physics Institute to drive a gas discharge [42]. The system was made possible by the detonation chamber used in Bichenkov's experiments [40]. The point of interest in this application of the bellows generator is the fact that a gas discharge is a resistive load. The load was matched to the generator via an air-core step-up transformer. Two variants of the experiment were devised: plasma created by an electric discharge from a capacitor bank and by an exploding wire in air.

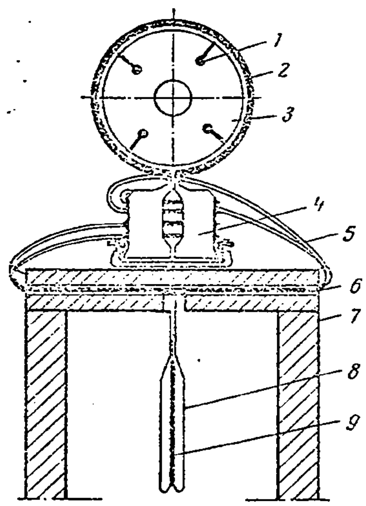

Fig. 11--Bellows generator in a detonation chamber driving a gas discharge plasma
1--electrode
2--steel single-turn primary
3--discharge chamber
4--collector
5--leads
6--electric bus
7--detonation chamber
8--bellows generator
9--HE cartridge

The following are the operational data for the bellows generator in a detonation chamber [42]:

High explosive	
Weight	200 g
Total energy	1 MJ

Generator	
Inductance, L_0	210 nH
Rail length	38 cm
Rail thickness	0.2 cm
Rail width	5 to 20 cm
Capacitor bank	
Capacitance	1.2×10^{-2} F
Voltage	3.5 kV
Peak current	440 kA
Transformer	
Primary	1 turn
Diameter	19.4 cm
Length	45 cm
Thickness	0.9 cm
Secondary	11 turns wound on discharge chamber
Discharge chamber	Plexiglas
Diameter	5 cm
Length	14 cm
Pressure	10^{-1} Torr
Operation using plasma discharge	
Current in primary	1.94 MA
Current in secondary	174 kA
Total energy to load	55 kJ
Including capacitor energy	15 kJ
Generator pulse length	50 μsec
System efficiency	5%
Operation using exploding copper wire connected by 8-turn transformer	
Wire length	11.5 cm
Wire diameter	0.01 cm
Energy delivered to plasma	10 kJ

C. DETONATION CHAMBER

The steel detonation chamber (Fig. 12) designed by Voytenko for indoor experiments with explosive magnetic-flux compression generators is of some interest. The chamber is designed to withstand shock pressures up to several hundred atm from high-explosive charges up to 3 kg.

The following are the basic parameters of the detonation chamber [40]:

Total weight	20 tons
External diameter	1720 mm
Height of cylinder	1720 mm
Wall thickness	160 mm
Thickness of cover 1	140 mm

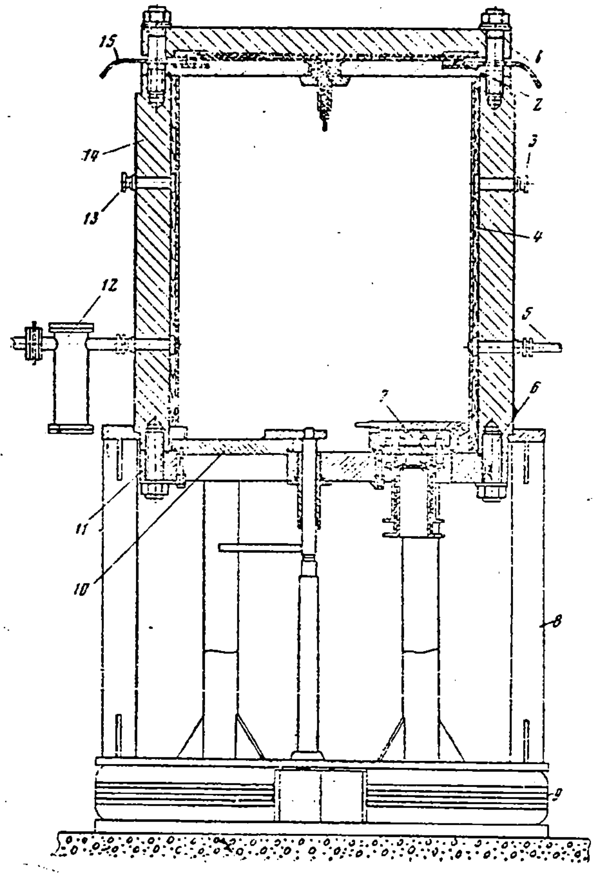

Fig. 12--Steel detonation chamber

Top cover 1 and bottom 11 are fastened to the cylinder body with 30 pins. Ports 7 and 10 are 340 mm and 500 mm in diameter, respectively. All seals are rubber gaskets seated in grooves. The chamber is not evacuated. The welded support 8 rests on four automobile tires 9. When tire pressure is reduced, the support plate drops several mm and comes to rest on metal lugs. Two-layer antifragmentation shield 4, made of a steel cylinder and wooden boards, completely protects the chamber walls from erosion. Exhaust tube 12 evacuates detonation products; compressed air is blown in through tube 5. Exhaust tube 12 has a remotely controlled valve. Port 7, with 12 airtight electric power leads, supplies the EMG unit. The total current to the EMG is 0.5 MA, 4 kV. The port also admits airtight coaxial cables. Plexiglas window 13 with polished end faces serves photographic needs. Electric cables 2 and 15 carry currents up to 2.5 MA, 5 kV from the EMG [40].

V. SUPERCONDUCTIVE ENERGY STORAGE

A. SUPERCONDUCTIVE MAGNET SYSTEMS OF THE INSTITUTE OF HIGH TEMPERATURES, MOSCOW

The Institute of High Temperatures (IVT), the principal institute of the Department of Physicotechnical Energy Problems, Academy of Sciences, USSR, was established in 1960 as a small high-temperatures laboratory at the Academy. Raised to the status of an institute in 1962, by 1974 it had become a major research facility. The scope of its research activities, ranging from basic research to prototype construction, includes studies of thermal and electrical properties of materials, heat and mass transfer, physical gas dynamics, new heat-resistant structural materials, direct conversion of heat into electrical energy, and new types of energy converters.

The institute's primary activity is the pioneering R&D of energy technology, principally MHD. A broad-based effort in MHD conversion began in 1963, near the start of the IVT's existence. Although mainly oriented toward the application of MHD to the production of commercial electric power, this effort has given rise to new research areas. The development of the U-02 and U-25 open-cycle MHD power plants, for example, led to and stimulated work on explosive MHD devices. (The only published account of the actual construction of an explosive MHD prototype concerns the VG-5 superconducting pulse generator [see pp. 73-75].) Other related areas include liquid-metal MHD systems and large superconducting magnets for MHD generators, the subject of this section [43].

The institute's research on superconductivity, initiated in 1962 and thus preceding even the R&D of practical MHD systems [43], concentrated from the beginning on the design of superconducting magnet systems for MHD power stations. The significance attached to this research program is underscored by the fact that it became a separate organizational entity in 1962-1963, when the Department of Applied Superconductivity was established at the IVT [44], probably under V. V. Sychev. The key members of Sychev's group are V. A. Al'tov,

V. V. Andrianov, M. G. Kremlev, N. A. Kulysov, F. F. Ternovskiy, and V. B. Zenkevich. Following the pattern of the institute as a whole, the Department of Applied Superconductivity pursues both basic research and the construction of prototype systems.

Official statements of purpose for the development of large superconducting-magnet and inductive-storage systems list such technological and scientific applications as MHD generators, large bubble chambers, large electric rotating generators and motors, topping cycles for electric power systems, emergency power sources, and sources of high-power pulses [45,46,47]. The target sizes of these devices are indicated by a number of references in 1971 and 1972 publications to such contemporary Western developments as the British 10^{13}-J topping plant project based on a superconductive homopolar motor in Fowley (England) and the bubble chamber at the Argonne National Laboratory, all mentioned by Sychev as indicators of the state of the art. According to Sychev, the magnetic field intensity achieved by superconducting magnet technology at that time (1972) was 15 tesla.

Theoretical Research

Early papers on superconductive solenoids dealt with the experimental investigation of the process of transition to the normal state and the effect of stabilizing winding [48]. The basic parameter in this work was the initial current in the solenoid. The stabilization structure in the early design was a copper coil wound together with the main superconducting coil and connected across a test resistor [49]. The range of investigation included also dissipation losses and the quantitative relationship between the current in the winding and the energy stored in the magnetic field [50]. Significant information on these effects was thought to be derivable from careful measurements of the solenoid inductance [51,52]. A special method, called the double-solenoid method, was developed for the experimental investigation of the propagation of the normal region in a superconductor. In particular, the method provided for highly accurate measurements of the currents in the composite strands of stabilized windings [53].

A high point in the work of the Department of Applied Superconductivity was evident in late 1971 and early 1972, when a fairly large number of publications marked the culmination of a cycle of research projects [43,45,47,54]. Although theoretical in nature, these projects essentially addressed the problem of the practical industrial use of superconducting magnet and inductor systems. Sychev listed at that time the following advantages of superconducting systems: no ferromagnetic core, higher current density and lower weight (by 2 to 3 orders), no joule losses and lower energy expenditure for internal needs (by 1 to 2 orders), no water cooling, much higher attainable magnetic fields, and much steeper gradients. The obstacles to the application of these systems included metallurgical difficulties in the production of superconducting alloys and intermetallic compounds, optimum magnet configuration involving minimum weight and maximum field intensity and field uniformity, compensation for mechanical forces on windings, refrigeration, methods of generating current, and the penetration of a magnetic field into the nonideal type II superconductors [55].

The central problem, the operational reliability of the superconducting windings, became the objective of a broad and comprehensive research effort by the Department of Applied Superconductivity [44,56, 57]. The problem was perceived from two viewpoints: (1) the prevention of superconductor transition to the normal phase, or at least the prevention of destructive transition, and (2) the realization of design parameters. The work completed between 1967 and 1971 concerned mainly the first aspect. An important milestone was the modernization of the Stekly model of a composite superconductor to account for the nonlinear nature of the heat transfer coefficient at the surface of the composite superconductor in a helium bath, the temperature dependence of substrate resistivity, and other factors [45,58].

Stekly's criterion of stability of the composite superconductor is

$$\alpha = \frac{\rho I_c^2}{AhP(T_c - T_b)} ,$$

where ρ is substrate resistivity, I_c is critical current at the helium bath temperature T_b, A is substrate cross section, h is heat transfer coefficient from the conductor to the bath, P is the perimeter of the conductor subject to cooling, and T_c is the critical temperature of the superconductor for the given magnetic field. If $\alpha < 1$, no transition to normal phase can occur, and the conductor is considered fully stabilized for all currents up to I_c. If $\alpha > 1$, the transition to normal phase is prevented only up to $I_m < I_c$. The value of I_m decreases with increasing α. In this case, the composite conductor is considered only partly stabilized.

The Stekly criterion, according to Sychev, is a simplified model of the process and fails to account for some factors affecting stability [59,60]. Sychev's basic contribution to the stability theory is the definition of the maximum equilibrium current I*, which marks the limit of equilibrium states in a composite conductor [45,56]. He has shown that if the superconductor becomes normal at I > I*, the temperature of the composite conductor increases without limit and the conductor burns out. Consequently, the maximum equilibrium current is an important criterion of reliability of a composite conductor. Its value is defined as

$$I^* = \sqrt{AhP/\frac{d\rho(T)}{dT}} \quad .$$

The concept of I* made it possible to explain the breakdown, reported in the literature, of a large fully stabilized superconducting magnet that burned out with current much lower than critical. According to a detailed analysis, the most probable cause of the burnout was a significant excess of current over I*. Experiments confirmed the existence of unstable equilibrium states of composite conductors with $\alpha > 1$ for $T < T_c$ and I*. The investigation of winding reliability covered the composite conductor in the following cases: (1) superconductor immersed in a relatively large volume of liquid helium; (2) low-density superconductor winding; (3) high-density superconductor winding, not permitting a ready access of liquid helium to the inner turns. Experimental studies of low-density

windings showed that a decrease in the helium bath temperature, especially with the use of helium II, decreased the relaibility of the winding [45,61]. High-density windings proved more reliable with respect to burnout but much less reliable in the breakdown of insulation [62].

Another milestone in the research on superconducting windings was the comprehensive investigation of the effective resistance of nonideal type II superconductors. The significance of this project derives from the problem of energy loss in superconducting windings operating with alternating or direct current subject to rapid changes.

Sychev stated in 1974 that the above projects involving superconductor stability had been completed. The problem of stabilization of composite superconductors is considered solved, and Sychev's team claims to have a fairly complete picture of the phenomena attending the initiation, existence, and propagation of the normal zone in the composite conductor windings of large superconducting magnets [43, 44,45,47,54,63,64].

The case of the 3.1-T superconducting magnet prototype built at the IVT illustrates the kinds of problems considered and the solutions achieved during the period when the Department of Applied Superconductivity was engaged in theoretical research. Despite the high current densities attainable in superconductors, available saddle-type windings were failing to realize this potential because of excessive structural reinforcements and large amounts of stabilizing metal, as a rule, copper. Sychev pointed to the example of an Avco-Everett magnet whose ratio of external magnet diameter to channel diameter was 4.7 and whose ratio of winding weight to structural element weight was 0.43. These ratios in a similar Japanese magnet were 2.6 and 0.41, respectively [65]. Noting that the proportion of copper could go as high as 100 to 1 in the attempt to ensure stability, IVT designers developed a 3.1-T cylindrical channel, 15 cm in diameter and 50 cm long, weighing only 102 kg [45]. The ratio of external to channel diameter had been reduced to 2.0 and the ratio of winding to structural element weight, to 1.5, for a magnetic field similar to that of the American and Japanese magnets [65].

Prototype Construction

The IVT has developed a series of superconducting magnetic systems with record parameters. The SMPS-1 system, designed to produce 4 tesla in a channel 30 cm in diameter and 1.2 m long, was nearing completion in 1974-1975. The windings, consisting of multistrand Nb-Ti composite cable impregnated with indium, carry a 1-kA current.

The somewhat greater detail available on the SMPS-0.5, a precursor of the SMPS-1, illustrates the technology involved in the construction of these devices. The SMPS-0.5 superconducting magnet consists of a saddle-shaped winding with a total length of 500 mm and an external diameter of 285 mm. The cylindrical channel of the cryostat is 100 mm in diameter. The winding, twisted composite cable impregnated with indium, consists of 21 superconducting and 28 normal copper strands. Each layer of the winding is protected by a belt of stainless-steel wire, eliminating the need for outer protective reinforcement and considerably reducing the weight of the winding. The current of 975 A induced a useful field of 3 tesla; the critical current was 998 A [43].

Similar windings were used in the superconductive inductive energy storage system developed after the series of experiments in which stored energy was successfully transferred to the Moscow power grid [45]. The inductive storage coil, supplied by a dc source, discharged into a three-phase inverter connected to the grid. Stored energy can be inverted, in principle, at either (1) constant average power or (2) constant average voltage at the coil terminals, the voltage being equal to the average counter-emf of the inverter. In the latter case, the rate of energy transfer is maximum for a given limiting voltage. The inverter can also be used as the external load working with large superconducting magnets in MHD generators, motors, bubble chambers, etc., when there is a probability of a hazardous condition, such as the initiation of a normal phase in the superconductor. Semiconductor inverters are considered much superior to the load resistors normally used for such purposes. Thanks to minimal energy dissipation, the semiconductor inverters have a significant advantage because, according to Sychev, modern magnet systems store energy on the order of 10^8 J, and 10^9-J storage coils are being built.

The experimental superconductive inductive storage system, incorporating a fast-acting semiconductor switch and the three-phase inverter, stored 10^4 J with an average current density of 8.4 kA/cm^2. In the discharge through the inverter, the discharge pulse length was 50 msec and the maximum current drop rate was 30 kA/sec. Nevertheless, a normal zone was not observed in the superconductor. On the other hand, the high rate of change of the magnetic field accompanying the discharge of the coil induced power losses reaching 20 percent, owing to the eddy currents in the metal parts of the cryostat. Dielectric cryostats would be preferable in these applications.

The following are the design details of the superconductive winding used in the system. The coil comprised 21 superconducting filaments of 65-BT alloy, copper clad, 0.3 mm in diameter, plus 28 copper filaments of the same diameter. To form the cable, three superconducting and four copper filaments were twisted together with a pitch of 10 mm, impregnated with indium, and insulated with "lavsan" plastic. The resulting seven strands were then twisted together with a pitch of 30 mm, impregnated with indium, and insulated with lavsan. The overall diameter of the cable was 3.5 mm. The frame of the coil was made of textolite milled to make cooling channels. The coil was wound in 12 layers of 78 turns each, the layers being separated from one another by 0.5 mm shims, forming channels for liquid helium. The channel width increased from 6 mm in inner layers to 10 mm in the outer layers. The coil dimensions were 60 mm in inner diameter, 144 mm in outer diameter, and 250 mm in length; the total weight with terminals was 15 kg. The winding ends were soldered to terminal plates, and the current bus was cooled over a length of 500 mm. The terminal plates, the bus, and the outer layer of the coil were carefully insulated. The coil was housed in a stainless-steel cryostat, 180 mm in internal diameter and 1400 mm high. The inductance of the coil was 0.022 H. The critical current of 947 A was independent of the current rise rate up to 130 A/sec [47].

B. SUPERCONDUCTIVE GENERATORS OF THE MOSCOW AVIATION INSTITUTE

Research on superconductive systems at the Moscow Aviation Institute (MAI) is being carried on by a team under A. I. Bertinov, whose key members are O. M. Mironov, A. V. Golovkin, and L. A. Yegoshkina. The research in superconductive magnetic systems at the Institute of High Temperatures is aimed at large magnets for MHD and pulsed-power uses; that of the MAI is oriented toward cryogenic and superconductive windings of rotating electrical machines for use in aircraft. Thus, although both institutes are engaged in the development of superconducting coils, the approach of each to the problem is quite different. The IVT is interested in very large magnets and high current. Consequently, it pursues the problems of stability of the superconducting state and stabilization of superconducting filaments. The MAI is interested in the dynamics of rotating magnetic systems and the effects of their magnetic fields on the adjacent electronic equipment aboard a tightly packed aircraft. However, the work on the theoretical and practical aspects of superconductive inductors being done at MAI has sufficient relevance to pulsed-power R&D to warrant a brief exposition. An example of the possible relevance of the MAI's work to pulsed-power applications (and an indication that the MAI is not dedicated exclusively to rotating machinery) is Bertinov's theoretical analysis of the large superconductive inductor discharging into the inverter built by the Institute of High Temperatures [66], discussed above. Bertinov was particularly interested here in the discharge process of such systems.

The rationale advanced by the MAI for its extensive R&D effort in superconductive electric machines is that cryogenic cooling and superconductive winding of these machines can considerably increase their power and efficiency limit while decreasing their weight and dimensions. The use of cryogenics calls for a design differing from the conventional in that, first of all, it dispenses with the ferromagnetic flux path. However, a superconducting synchronous machine without a ferromagnetic core projects intense magnetic fields that can affect electronic equipment in the vicinity [67]. This makes it necessary to shield the magnetic field of such a machine with

ferromagnetic or diamagnetic screens. The effect of such shielding, in turn, increases the magnetic field intensity inside the shield. The absence of the ferromagnetic core and the various effects of shielding call for new methods of analyzing magnetic fields in superconductive generators and motors. According to Bertinov and Mironov, the experimental data available in 1974 on such machines were still inadequate for the formulation of the best methodological approach to the analysis [67,68,69].

The thrust of the MAI's research in this area during the past six years has been the development of such analysis. The research involved the study of dynamic models of superconductors using conformal mapping as a method of determining magnetic induction [70], the calculation of inductances in shielded windings [71,72,73], the analysis of forces acting on the rotor and due to eccentricities in shield placement [69], and the determination of the maximum magnetic field in the region of superconducting multipole inductors [74]. Transition to the normal state was considered from the viewpoint of reliability only in terms of current density [75]. The following critical parameters of the superconducting cable were considered:

1. Current density and the corresponding magnetic field intensity
2. Current rise rate with changes in the operating regime
3. Excess of superconductor temperature over liquid or gaseous helium temperature in the presence of ac losses

A diagram of state of the superconducting winding was developed as a means of determining the current density range in which the hazard of transition to the normal state can be avoided [74].

The MAI is not concerned with the problem of stabilization of superconductors, probably because the synchronous generators for use in aircraft are generally smaller than the inductors investigated by the IVT for MHD and other scientific and technological uses.

C. SUPERCONDUCTING INDUCTIVE STORAGE DEVICES OF THE YEFREMOV INSTITUTE OF ELECTROPHYSICAL EQUIPMENT, LENINGRAD

A research team at the Yefremov Institute of Electrophysical Equipment has been pursuing both theoretical work and the construction of prototypes in the area of superconducting inductive storage devices. The key members of the team are N. A. Monoszon, F. M. Spevakova, and A. D. Frolov. The explicit application of superconducting storage inductors was experimental controlled-fusion research. According to the Yefremov team, superconducting inductors become more economical than capacitor banks at energy levels of 10^7 J and above. Inductors with a storage capacity of 10^8 to 10^{10} J are expected in the near future [76].

The team's theoretical work was slanted toward engineering considerations of designing superconducting inductor systems, including selecting optimum system geometry and ensuring the minimum cost of superconducting materials per unit of stored energy. The results of the basic evaluation of stabilized winding structures were applied to the design of prototypes for 30, 80, and 230 kJ [77]. The winding cable for each of the three prototypes consisted of six superconducting Nb-Ti composite strands and one copper strand, with an overall copper-to-superconductor ratio of nearly 10 to 1. The cable was impregnated with indium and packed with cotton insulation. The principal parameters of the three prototypes are shown in Table 1.

The design of the prototypes allowed for cooling by submergence in a tank of liquid helium and by the circulation of liquid helium in copper pipes on the surfaces of the windings. In the 30-kJ winding, cooling pipes were also passed through the core.

The Yefremov Institute has been reported [77] to be going beyond these prototypes with the development of superconducting inductive storage devices for 0.3 and 1 MJ at 10 kA and inductors capable of withstanding a magnetic field rate of change of 100 to 150 kG/sec without transition to the normal state.

Table 1

PRINCIPAL PARAMETERS OF THREE PROTOTYPE STORAGE DEVICES

	Prototype Storage Device		
	30 kJ	80 kJ	230 kJ
Winding			
Inside diameter (cm)	4	22	30
Outside diameter (cm)	18	32	40
Height (cm)	28	18	32
Inductance (H)	3.6×10^{-2}	1.6×10^{-1}	2×10^{-1}
Maximum field (kG)	60	42	43
Maximum calculated current (A)	1300	900	1500
Composite wire diameter (mm)	1	0.5	0.85
Superconducting wire thickness (μm)	120	60	75

VI. HOMOPOLAR MACHINES

The basic requirement of pulsed-power sources is the capability to transfer considerable quantities of energy to inductive loads within limited time intervals and to maintain this energy at a constant level for a relatively long period. Four types of energy storage have been considered for this purpose: the electric field of large capacitor banks, the magnetic field of induction coils, the kinetic energy of a rotating mass in electrical machines, and the chemical energy of storage batteries. Of the four types, capacitive storage remains the principal one used in research requiring high pulsed power. Rotating machinery, however, has considerable appeal as an alternative energy source because of its high energy-storage capacity. Given a rotor with a stored energy density of 75 to 100 J/cm^3, it is possible to obtain usable energies far exceeding the comparable values of the other types. Conventional commutator machines with large flywheels, however, must be specially built to withstand the stresses associated with short pulses. For this reason, homopolar generators are more suitable than the conventional machines in some pulsed-power applications.

A major theoretical and experimental R&D program on homopolar machines has been under way at the Moscow Aviation Institute during the past two decades. A. I. Bertinov, B. L. Aliyevskiy, V. L. Orlov, A. G. Sherstyuk, and other members of the MAI team have been developing a wide range of rotating electrical machinery capable of delivering high energy densities. In their view, homopolar air-core machines are especially suitable for the application of cryogenic technology and superconductivity to advanced electrical equipment. Specifically, homopolar air-core generators with liquid-metal current collectors can be used as the power supply for high-magnetic-field devices in MHD pulsed-power research.

The use of homopolar generators with MHD pulsed-power devices was the context of an early (1967) basic analysis of the performance of these machines [78,79]. The primary objective of the analysis

was to compute the emf of cylindrical and disc types of homopolar machines, either by integrating the magnetic field over the active region of the rotor or by applying the method of mutual inductances between the inductor and rotor windings. Previous approaches to this problem resulted in a considerable number of errors from neglecting the finite cross-sectional area of the annular coils.

The high current in homopolar machines requires thick-walled armatures, which, in turn, cause a nonuniform current distribution. Nonuniform distribution increases the armature loss and resistance. Consequently, in the case of hollow rotors, the computation of efficiency and thermal balance of homopolar machines requires a correction factor based on the actual distribution $j = j(r,z)$. It was assumed in the early analysis that μ and conductivity are constant for a nonferromagnetic rotor and that therefore the rotor represents a linear medium. The current distribution in the rotor was determined by superposition of the open-circuit mode ($j = 0$) and the short-circuit mode, where an equivalent voltage source was assumed at the terminals. It was estimated that for short rotors ($\ell/R \leq 3$, where ℓ is length and R is radius), power loss and resistance were 1.5 times higher than the values obtained on the assumption of uniform distribution of current density in the active region (between collectors). In comparatively thin disc rotors, current density was assumed to be uniformly distributed over the cross-sectional areas normal to the radius. In constant-width discs, $j = j(r)$ is inversely proportional to the radius [80]. In conical discs, the lowest current density is reached at some point between the axis and periphery [78].

The correction factor accounting for the increased rotor loss and resistance due to the nonuniform current distribution was also calculated (by I. A. Krynitskaya [81]) for the case of a segmented collector of a cylindrical hollow rotor. The correction factor depends on the number of segments in the collector and on the structure of the rotor.

These methods were later found to be not accurate for the contemplated applications of homopolar machines. These applications

to "various areas of technology" (in Aliyevskiy's words [82]) and the problems of designing economically realistic high-power homopolar machines featuring superconductors and highly pure metals in their inductors were found to require exact methods of analysis. In 1972, Aliyevskiy published what he claimed was the first general method of calculating the dimensions of air-core rotors for homopolar machines and of optimizing the geometric parameters of the annular inductor [82]. Numerical computation methods were used in the analysis to produce a series of nomograms yielding the optimal dimensions of inductors for cylindrical and disc machines, given a relative emf. Calculations by this method, claimed to be both more universal and more accurate than the previous calculations, produced results that were in good agreement with experimental data.

The effect of nonuniform current distribution was further considered in 1974. It was again assumed that the rotor was a linear medium with constant μ and conductivity (uniform heating). The obtained correction factor was applicable to the resistance, power loss, and voltage drop of a rotor on the assumption that the ring collectors were located asymmetrically with respect to the median plane of the rotor. The resulting current distribution functions were also applicable to the analysis of the demagnetizing effect of the transverse rotor reaction in a ferromagnetic rotor. The correction factor was found to decrease with increasing rotor length and to be equal to unity in rotors whose length-to-radius ratio was 3, typical of homopolar motors without ferromagnetic cores [83].

Parallel to his computations involving the electric power losses and geometric parameters were Aliyevskiy's calculations of the electromagnetic forces acting on the inductors of homopolar machines. In an approach generalized to various types of inductors, he used the method of equivalent circuits to compute the radial and axial forces acting on bilateral air-core inductors. These may be two axially symmetric circular or rectangular coils and they may differ in size. The forces were computed as functions of cross-sectional area and separation between the coils [84].

Bilateral inductors with ciruclar coils are said to be typical of both coaxial MHD generators and homopolar machines. Bilateral inductors with rectangular coils are typical of linear MHD generators

and MHD accelerators. In 1974, Aliyevskiy's force computations were rendered more precise by the integration of the volumetric density of electromagnetic forces [85], yielding a recommended ratio of the axial force component in a bilateral inductor. A fairly exact computation of the electromagnetic moment of the rotor was also generalized to any configuration of contacting surfaces. The reactive moment in homopolar machines, in contrast to that in conventional air-core machines, acts on the current-collector system of the rotor and not on the inductor coils. The computations were facilitated by the development of an expression for the azimuthal component of the vector potential of the magnetic field [86] and for the radial components of the induction vector. A large number of computer runs performed on the NAIRI-2 computer yielded results that agreed with the experimental data and with the results of calculations by other methods [85].

The MAI's concern with the electromagnetic effects of rotating machines on nearby sensitive equipment has led to the development of ferromagnetic and diamagnetic shielding, which is particularly important for superconducting inductors. Such shielding serves in many applications to localize magnetic field within a required region; in homopolar machines, ferromagnetic shielding of magnetically soft steel tends to increase the active magnetic flux. Aliyevskiy gives solutions of boundary value problems for different standard shapes of ferromagnetic and diamagnetic shields [87]. These are idealized shapes (infinite plane, two parallel infinite planes, and cylinders), but the solutions are claimed to be sufficiently general and accurate to be applicable to specific engineering problems.

The above account of MAI work on homopolar machines indicates a systematic if narrow progress of inquiry. It is known that the MAI built experimental prototypes of homopolar generators in the early sixties [88]; however, no further information on such construction has been forthcoming. Inasmuch as the MAI has continued its related theoretical and experimental work on homopolar machines, it is

unlikely that it has stopped building experimental models. One possible conclusion is that homopolar machines built by the MAI after 1965 were considered too sensitive to be discussed in open-source publications. A recent paper by Aliyevskiy [89] may be interpreted as tending to reinforce such a conclusion. The paper analyzes the British-made IRD superconducting homopolar machine "to acquaint a broad community of electric machinery designers with a promising dc machine of a new type." Since, according to Aliyevskiy, the published technical specifications of the British machine were inadequate, he decided to analyze the machine in detail, using the methods developed during the course of the R&D effort in this area at the MAI. Aliyevskiy claimed that his analysis provided complete details on the machine consistent with the known specifications. The British machine appears to have served as a verification model for Soviet theoreticians.

The British IRD homopolar motor has a superconducting inductor and is rated at 2.4 MW. Aliyevskiy states that it is the first industrial superconducting magnet machine in Europe with an inductor of that size. Such a machine would be an interesting object of the kind of theoretical exercise presented in Aliyevskiy's paper. The implications of this exercise, together with Aliyevskiy's statement on the need to acquaint Soviet designers with a new type of machine and the lack of any publications on advanced Soviet homopolar machines, could be taken to mean that the Soviets simply have not developed a comparable practical design. On the other hand, as noted above, the MAI has been working with homopolar machines for over a decade and, during a comparable period, has in addition been maintaining an even greater effort, involving Bertinov's close participation, to develop superconducting generators and motors. It would not be unexpected, therefore, to see these closely associated groups within the same organization make some attempt to apply superconducting technology to homopolar machines. It would be equally reasonable to expect to see references to such an attempt in a published paper on the application of the Soviet research experience to the analysis of a foreign machine. Aliyevskiy's paper, however, contains no such

references. It may be concluded, therefore, that (1) the British design was used as a vehicle for discussing the hardware aspects of homopolar machines in conjunction with Soviet theory and (2) the Soviet hardware aspects of advanced homopolar machines were considered too sensitive for publication and could not be used in support of Soviet theory.

The MAI contribution to the published literature on homopolar machines is not paralleled by that of any other Soviet research institution. The few significant papers on this subject emanating from other research organizations indicate that some R&D work on homopolar machines is being done by the Yefremov Institute [90] in conjunction with the Leningrad Polytechnic Institute (LPI) [91,92,93]. V. A. Glukhikh and B. G. Karasev reported on the Yefremov Institute's homopolar work; V. V. Kharitonov and V. M. Yurinov on the LPI's. According to these accounts, the work involves theoretical and experimental studies of pulse homopolar generators to serve as a basis for the design of high-power machines to supply power to "various kinds of electrophysical equipment."

One such prototype machine is a disc-type generator with a rectangular frame core and liquid-metal current collectors. The generator has two rotors, 1 m in diameter, rotating in opposite directions at 2800 rpm and capable of storing 4 MJ with a short-circuit current of 700 kA and peak power of 25 MW. In the design stage are 40- and 100-MJ homopolar generators intended as the power supply for inductive energy storage devices [90]. A recent LPI paper [91] deals with the theoretical aspects of the regulated excitation flux in a drum-type generator. The flux regulation is required for shaping current pulses in the discharge of the generator. The problem is posed by the eddy currents in the massive generator core which affect the transient pulse-shaping process. The paper presents an approximate analytical solution, noting that more exact solutions require the use of computer codes.

The transient processes in homopolar motors were investigated by another Leningrad group (whose institutional affiliation is not known), consisting of V. I. Andreyev, A. I. Khozhainov, and S. Ye.

Kuznetsov [94]. According to this group, homopolar motors can be used in autonomous transport vehicles with low-voltage power supply from storage batteries, solar batteries, thermoelectric generators, etc. The requirements of simplicity and reliability can be met by the total immersion of the rotor in liquid metal (mercury, NaK, etc.) serving as the current collector. A small-scale experimental prototype was built to study the effect of the boundary layer of the liquid metal on the transient characteristics of the motor.

VII. MULTIPOLAR PULSE GENERATORS

Rotating electric machines used for the generation and storage of pulse energy are attractive because of the large storage capacity in the inertial mass of the rotors, the portability of systems driven by low-power sources, and the reasonable weight and size. Energy storage in rotating flywheels is more economical than capacitive or inductive storage. The energy transfer from the rotating mass to the inductive load poses less of a switching problem than energy transfer from a capacitor bank or from an inductor. Another advantage of these devices is that their basic design principles have been in general industrial use for many years, so that these generators are much better known than all other pulsed-power generating equipment.

Specialists at the Institute of Automation and Electromechanics of the Tomsk Polytechnic Institute (TPI) consider bipolar machines superior to homopolar generators in the available power density and the necessary switching techniques. Multipole pulse synchronous generators can deliver over 100 MJ [95], making them useful, first of all, to pulsed energy users operating with msec pulse lengths under stationary conditions [96]. TPI researchers do not specify the applications of the pulsed-power generators beyond stating that "modern experimental physics is finding increasing uses for megajoule millisecond pulsed magnetic fields" [97]. The generators are said to be most suitable for fast discharge into inductive or resistive loads in time intervals equal roughly to one voltage period.

Key members of the group at the TPI Institute of Automation and Electromechanics, G. A. Sipaylov, A. V. Loos, V. V. Ivashin, and Yu. A. Romanov, have been publishing steadily on the subject of synchronous pulse generators since the late fifties [98]. Theirs is a theoretical and experimental effort involving the design of novel generating systems, according to a series of patents (author's certificates) granted over the years [99,100,101,102,103,104]. Rather than building their own generator prototypes for use in their research,

however, they appear to be using machines built by the Elektrosila plant. The main thrust of their work is the design and prototype construction of inductive storage systems comprising generator-switch-load combinations, aimed at increasing the efficiency of utilization of the energy stored in the rotors.

The disadvantage of pulsed-power rotating machines is the small fraction of stored energy that can be transferred to the load during one half-period of the ac voltage. This can be improved slightly with the use of a single-phase pulse generator. However, even such a generator cannot deliver in a first pulse more than 5 to 10 percent of the energy stored in the rotor. The fraction of delivered energy can be further increased by using several positive half-periods for energy transfer to the load. This, in turn, calls for sophisticated sequential switching of kA currents [105]. Another improvement developed by the TPI is the acceleration of the accumulation process by means of a capacitor bank connected in parallel with the load [96,100]. The peak energy deposited in the load can be several times higher than the energy of a single pulse of the generator, and may reach several hundred MJ in very large machines.

Finally, the pulsed power of multipole generators can be increased by boosting, or forcing, the excitation field, if the boost does not lead to the loss of stored kinetic energy and the overheating of the machine. Patents were granted for a number of field-forcing methods [101, 102, 103]. The first of these used an asymmetric rotor winding and an auxiliary stator winding, shifted 90° with respect to the main winding [101]. When the auxiliary winding is shorted at zero emf, the main magnetic flux is boosted, increasing the emf of the main winding. The load is connected when the main winding emf goes through zero. A modification of the field-forcing method combines a winding and a switch circuit designed to close at the point of maximum flux linkage. The highest boost is achieved by mounting the auxiliary winding in the rotor. The usable energy density of such machines should reach 600J/kg [96].

Different problems exist with resistive loads. The energy delivered to a resistive load cannot be returned to the generator at the end

of the pulse, as is the case with inductive loads, because to do so would alter the speed of the rotor and affect the operation of the generator. The TPI group is therefore studying the variation of generator speed. A set of performance characteristics for the case of a single-phase pulsed generator supplying resistive load has been developed in the course of an extensive computer analysis. The resulting characteristics were applied to the TI-200-2 generator as an example of energy calculation. The generator, rated for 200 MVA, was found capable of delivering 54 MJ to a resistive load [106].

Research at the Leningrad Polytechnic Institute has closely paralleled that at the TPI, although apparently on a smaller scale [107]. No sustained series of publications nor distinct group of authors is discernible. The Leningrad, like the Tomsk, specialists were attracted to rotating machinery for pulsed-energy storage as an alternative to capacitive storage, at the time (1965) the predominant storage method. The LPI effort, located at the High-Voltage Engineering Laboratory, concentrated on the following areas:

1. Synchronous pulse generators. For generators available in the USSR, such as the TI-75, the energy transferred to the load was limited to 3.18 MJ by a reactor built into the generator. The usable energy could be increased to 4.78 MJ by removing the reactor and installing reliable, fast-acting switches. For such generators, the LPI used a measure of effectiveness defined as

$$\eta = \frac{\Delta W_1}{\Delta W_0}$$

where ΔW_1 was the energy transferred to the load, and ΔW_0 was the energy transferable to the magnetic field of the machine by shorting its terminals. For the switch-equipped generator, $\eta = 1.5$.

2. Machine-capacitor storage system. This system was expected further to increase the ratio η. In combination with a 0.3 MJ capacitor bank (about 10 percent of W_0), the TI-75 generator could deliver 8 MJ at $\eta = 2.5$. This system could not only transfer to the load all the energy stored in the capacitor bank, but could also considerably boost the effectiveness of the generator. A combination

of two TI-200-2 machines and a 12.6 MJ capacitor bank could concentrate 30 MJ in the load.

3. Inductive storage. The most economical way of storing energy in an inductor is to use a pulse generator that is repetitive and supplies power to a series of inductors. A switching system delivers energy from the three-phase generator sequentially to each inductor within one period of the pulse. In a series of pulses, all inductors can be saturated [107].

The application of this work, according to the LPI, was to plasma physics studies. The objective was to transfer considerable energy to an inductive load in a limited time interval and to maintain the energy at a constant level for a relatively long time [105].

VIII. PULSED MHD GENERATORS

Soviet R&D of pulsed MHD generators ranges from exotic concepts, such as MHD channels coupled to thermonuclear detonating chambers and fissioning-gas reactors, to straightforward concepts, such as pulsed supersonic channels operating with nonequilibrium plasma, and includes work on superconducting magnet systems. The principal investigative facilities are the Institute of High Temperatures and the Kurchatov Institute of Atomic Energy. In addition, significant work has been done at an unidentified institute in Novosibirsk, as well as at a branch of the Institute of Chemical Physics working together with the Institute of High Temperatures.

The Kurchatov Institute of Atomic Energy has been pursuing the more advanced and even esoteric ideas proposed by Ye. P. Velikhov and V. S. Golubev. Most of this work appears to be still in the theoretical stage. On the other hand, at the Institute of High Temperatures, under the direction of A. Ye. Sheyndlin (head of the IVT) and Academician V. A. Kirillin, the more practical designs have led to working prototypes. These designs were developed in part as a spin-off of the IVT's ongoing major program for the construction of large commercial MHD electric power plants.

The Kurchatov Institute appears to provide the real driving force for the development of exotic pulsed MHD devices and their application to various physics problems and technologies requiring very high energy densities. Consequently, it is the Kurchatov Institute that could be expected to lead the development of pulsed MHD systems for military applications. An example of the Kurchatov's leadership in the development of exotic MHD systems that have actually been realized operationally is the PAMIR-1 30-MW generator, used for seismic prospecting and earthquake prediction. The PAMIR-1, in terms of portability and output power, has no equal in the West. Having a 3-sec operating period, however, it is not a true pulsed system and therefore is not covered here.

The Institute of High Temperatures, on the other hand, is dedicated largely to the development of MHD systems as generators of commercial electric power. In its work, the IVT has accumulated a considerable fund of experience that has been useful to Kurchatov scientists. Particularly impressive at the IVT are V. V. Sychev's designs of superconducting magnet systems for MHD generators (the details of which are discussed here only to the extent of their application to pulsed MHD).

The overall Soviet effort in this area is surveyed below in the context of three distinct research thrusts: optimization of power output and system efficiency, application of superconducting magnet systems to explosive MHD generators, and MHD systems driven by nuclear energy.

A. POWER OUTPUT AND EFFICIENCY OF PULSED MHD SYSTEMS

The Kurchatov Institute team investigating the power output and system efficiency of pulsed MHD systems includes V. S. Golubev, A. D. Belykh, and V. A. Gurashvili. They used a pulsed supersonic MHD generator operating under conditions of nonequilibrium ionization in their parameter optimization analysis. According to Golubev, the basic problem in designing an MHD generator with nonequilibrium conductivity is the establishment of a self-sustaining electrical discharge in moving gas. In such a discharge, the electrons are heated by the induced field uB, where u is the gas velocity. The difficulties associated with this process include large plasma inhomogeneities and the need for a preionizer to generate a homogeneous plasma. Such a process, yielding a nonequilibrium conductivity of 100 mho/m, can be established in a disc channel. The disc geometry permits the current heating the electrons to close on itself in the gas. The nonequilibrium conductivity process runs as follows. The equilibrium conductivity at the channel inlet, corresponding to the gas temperature, is 10^{-5} mho/m. Gas is preionized at the inlet by auxiliary arcs, establishing a conductivity of 100 mho/m, which is then maintained solely by the induction field [108].

Golubev began a series of experiments in the 1960s to prove the feasibility of achieving a high power level (of the order of megawatts) at the load, with nonequilibrium plasma. Specifically, he intended to disprove the contention of B. Zauderer of the United States, who said at that time, that only 10 percent of the gas enthalpy could be converted into electrical energy and that physical limitations, such as shock waves, internal short circuits, and boundary layer detachment, precluded higher efficiencies.

Golubev's experiments were carried out with the system called the shock tube, consisting of low-pressure chamber connected to an MHD channel with 15 electrode pairs. The following are some of the experimental parameters:

Working fluid	Ar + 0.1% Cs
Stagnation temperature	5000 to 7500 K
Stagnation pressure	16 to 20 atm
Mass flow	1.5 to 2 kg/sec
Pulse length	1.5 to 2 msec
Magnetic field intensity, B . . .	2 to 4 tesla
Inlet Mach number	2.5
Outlet Mach number	3.3
Cesium density	10^{16} cm^{-3}
Output power	1.5 MW
Maximum electrode voltage	400 V

The electrodes, 2 x 4 cm, set 4 cm apart, were made of tungsten copper alloy uniformly perforated with 1.2 mm holes for weak suction of the boundary layer. For B = 4 tesla and static temperature in the channel T_{st} = 2500 K, the electric power output was 1.5 MW, amounting to 20 percent of the plasma flow enthalpy. No shock waves were observed because of the high velocity, the boundary layer suction, and the nonstationary mode of flow in the channel. Golubev concluded that an MHD generator under conditions of nonequilibrium conductivity should, in principle, be capable of extracting up to 30 percent of the flow enthalpy [109].

The shock tube experiments were recently repeated (with largely the same parameters, except that the stagnation temperature extended to 9000 K and the stagnation pressure range was 14 to 20 atm) to try to achieve the predicted 30 percent efficiency. Golubev used the

"turbulence" formula to determine the effective plasma conductivity:

$$\sigma = \frac{e\langle n_e\rangle \beta_{eff}}{B} ,$$

where β_{eff} is the effective Hall parameter;

$$\beta_{eff} = \frac{\langle E_x \rangle}{\langle uB - Ey \rangle} .$$

In the experiments, the value of σ was computed from measured values of n_e and β_{eff} and compared to the experimental values of σ. The difference was found to be within experimental error. The value of σ was in the vicinity of 0.3 mho/cm. The efficiency of energy conversion was defined as

$$\eta = \frac{W_1}{c_p GT} ,$$

where W_1 is the power delivered to the load, c_p is heat capacity at constant pressure, G is mass flow rate, and T is stagnation temperature. The highest values of η were obtained at 9000 K for an output power ranging from 2.5 to 1.7 MW, depending on the load resistance. Under these conditions, the efficiency was close to 30 percent.

Golubev attributed this high value to the nonstationary nature of the MHD flow. The separation of the boundary layer and the resulting shock may indeed occur at some level of kinetic energy of the gas flowing in the channel. However, no shock was observed in the experiments, mainly because the characteristic time of flow stabilization was too short for the development of the boundary layer and its separation [110].

A team of Novosibirsk researchers of unknown affiliation, consisting of V. V. Polyudov, V. P. Titov, G. A. Shvetsov, and Yu. A. Burenin, conducted a similar, although purely theoretical, study of the limits of output power and efficiency, using explosive conduction-type MHD generators [111,112]. Again, the starting point of the study was the attempt to disprove conclusions of United States

researchers, this time H. J. Pain, P. R. Smy, and R. L. Conger, concerning the limits on the possible energy and power delivered by pulsed MHD generators.

Pain and Smy, analyzing the energy characteristics of MHD generators for $R_e >> 1$, concluded that the distortion of magnetic field in the MHD channel by moving plasma imposes a limit of $2B_0^2\mu_0$ on the stagnation pressure, where B_0 is the initial magnetic field. It follows that both power and energy are also limited to $4W_0u_0/\ell_0$ and $4W_0$, respectively, where W_0 is the initial magnetic field energy and ℓ_0 is the length of the channel. Conger established a similar limit on the energy delivered to a resistive load of a magnetic flux compression generator, the limit being $W_0\ln(L_0/L_1)$, where L_0/L_1 is the ratio of initial inductance of the generator to the load inductance.

The Novosibirsk team assumed that in the operation of explosive MHD generators, the generator resistance R_g, load resistance R_1, and the rate of change of total inductance are (1) variable quantities and (2) functions of the energy being generated and also of the location of the plasma slug in the channel. Therefore, an exact solution of the voltage and energy equations cannot be obtained. Nevertheless, useful relationships can be determined from the simplifying assumption that the resistances and dL/dt are constant. The simple solution thus obtained or the energy balance depends on the quantity $\gamma = (1/R)(dL/dt)$. For $\gamma << 1$, the energy of the system indeed does not exceed $2W_0$. However, for $\gamma > 2$ and above a certain value of L_0/L_1, the maximum energy of the system can exceed $W_0\ln(L_0/L_1)$ considerably. When $\gamma >> 2$, the energy of the system increases mainly as a result of the magnetic field energy, the rate of increase being limited by L_0/L_1. When $R_1 >> R_g$, the energy can be transferred to a resistive load.

In a specific case of a conducting piston moving in an MHD channel of constant cross-section, in an external magnetic field B_0, the ratio ε/W_0 (ε is the energy transferred to a resistive load) is shown to reach a peak of ~7 for $\gamma \approx 3$ and $L_0/L_1 = 50$. This is claimed to demonstrate that for $\gamma >> 1$, the energy transferred to a resistive load may exceed significantly the published limits on such transfer.

In real cases when $dL/dt \neq$ const., the energy conversion process can be represented as a series of time intervals within each of which dL/dt = const. Within each interval, therefore, the energy relationship is the same as in the idealized case. In a general case, dL/dt is a function of piston velocity and channel geometry. For a generator with constant cross section, the condition that dL/dt = const. is equivalent to that of v = const. However, if the piston velocity is constant, only a small fraction of the kinetic energy will be converted into electrical energy and the efficiency η will be close to zero. As the piston velocity decreases, η increases; but this also decreases dL/dt and consequently ε/W_0. One way of solving this problem is to compensate for the decreased piston velocity by a suitable change in the channel geometry. A more fundamental solution would involve a simultaneous optimization of both η and ε/W_0 [111].

The Novosibirsk team recently considered such a simultaneous optimization of η and ε/W_0. Their approach was to regard the energy transferred to an inductive-resistive load as a function of η under conditions where η can approach unity. The simultaneous provision of high-efficiency conversion of explosive-to-electromagnetic energy and a maximized ratio of load energy to magnetic energy would eliminate the need for large high-explosive charges and large external sources of initial magnetic field.

The team used a simple conduction MHD model to obtain the sought energy relationships. The model postulated a nondeformable zero-resistance piston, decelerating in the channel during its interaction with the magnetic field. The piston was thin in relation to the channel length and the electrodes were ideally conductive. The approach was based on a series of nomograms representing the relationships among the system efficiency η, the energy of the initial magnetic field W_0, the total magnetic energy W in the circuit, and the energy ε delivered to a resistive load. By postulating a self-excited or externally excited generator configuration, the type of load (predominantly resistive or inductive), and the desired

efficiency, one can determine the optimum parameters of the system in terms of load resistance R_1, generator inductance L_g, piston velocity v, initial magnetic field B_0, and electrode length ℓ. The criterion quantity is the ratio

$$P = \frac{R_1 L_g}{\ell v} \quad .$$

According to the nomograms, as η increases from 0 to 1, the load energy ε increases slightly and total energy $\varepsilon + W$ decreases slightly as long as P remains small. The rise in ε and drop in $\varepsilon + W$ become larger with increasing P [112].

B. EXPLOSIVE MHD GENERATORS WITH SUPERCONDUCTING MAGNET SYSTEM

The Institute of High Temperatures conducted a major study of explosive MHD generators with superconducting magnet systems in 1967-1969. The study team, led by V. V. Sychev, included V. A. Al'tov, E. I. Asinovskiy, and V. B. Zenkevich. Academician V. A. Kirillin was also associated with this work. The explicit purpose of the study was the "urgent need" to develop autonomous sources of electrical energy capable of delivering hundreds of megawatts in a few milliseconds. According to Sheyndlin, the use of superconducting magnet systems would significantly improve generator performance and ensure long operating periods without auxiliary energy sources.

The basic development problem considered by the IVT team was the behavior of the magnetic system during the strong interaction between magnetic flux and plasma flow. The passage of the plasma slug through the MHD channel delivers a considerable mechanical blow to the magnetic components of the system. The blow is taken in part by the external metal shell of the dewar. But because the electrical resistivity of the internal dewar wall is much lower than that of the external shell, the characteristic damping time of eddy currents in the internal wall is long, and the blow is transmitted to the liquid helium and, thus, to the winding of the magnetic system.

The plasma slug also produces a current surge in the shorted superconducting winding. The energy dissipation resulting from the mechanical blow and the current surge may lead to the restoration of the normal state in the superconducting winding. A further complicating factor is the impossibility of surrounding the relatively small superconducting magnets with sufficient normal metal (Cu or Al) to fully stabilize them. If windings are not fully stabilized, high current density is reached in the normal metal at the expense of decreased current density in the superconducting material. The appearance of a nucleus of normal region in such windings causes an uncontrolled transient process liberating all the stored magnetic field energy as heat.

The first series of IVT experiments was done in a shock tube using discharge plasma as the medium; later experiments involved the detonation products of high explosives. In the shock tube experiments, an 11-KJ capacitor bank produced a shock wave with a conductivity of a few mho/cm, traveling at 5 km/sec. The peak power of the generator ranged from 10 to 100 kW, depending on the load, in a pulse of 450 μsec with open circuit and 150 μsec with a 0.1-ohm load [113]. The second series of experiments involved the use of high explosives instead of the discharge plasma [114]. The system was modified for this purpose in 1968 and designated the VG-5. The resulting peak power was 1.2 MW in a 35 μsec pulse at 3.46 kA, from a high explosive developing 87 kJ.

The superconducting magnet system consisted of 4 copper spheres 270, 310, 370, and 400 mm in diameter; the innermost sphere was filled with liquid helium and contained the winding. The latter consisted of two identical coils placed symmetrically on either side of the channel. Each coil consisted of 1570 turns of a 6-strand 65-BT superconducting Nb-Zr-Ti cable, the superconducting strands wrapped around a seventh stabilizing strand of normal copper, all strands being 0.27 mm in diameter. The strands were twisted, impregnated with high-purity indium, and insulated with plastic. The total weight of the superconducting magnet system was 16 kg. The cylindrical

stainless-steel detonation chamber was smoothly joined to the rectangular stainless-steel MHD channel. The detonation chamber volume was 0.3 liter; the dimensions of the channel were 49 x 17 x 590 mm. The MHD channel cross section was later modified to 35 x 70 mm^2; the length of the uniform magnetic field section was 150 mm [115]. The copper electrodes were continuous, with a length of 500 mm.

The high-explosive charge was 15 g of hexogen with 1.5 percent by weight of potassium picrate. The plasma slug resulting from the explosion had an average velocity of 8.3 km/sec and was 3 cm thick. The explosion products were dumped into a 17-liter reservoir. The following were the operating parameters of the VG-5 system:

Peak voltage	350 V
Peak current	3.46 kA
Peak power	1.5 MW
Pulse length	35 μsec
Magnetic field in channel	1.5 tesla
Electrical conductivity of plasma	18 mho/cm
Total energy of plasma slug, W	420 J
Mechanical energy of slug in magnetic field, A . .	40 J
Plasma joule loss, Q	20 J
Energy delivered to load, E	20 J
Electrical efficiency, (A - Q)/A	50%
Mechanical efficiency, A/W	9.8%
Total system efficiency, (A - Q)/W	4.8%

In the course of the experiment, the current continued to flow in the magnetic system for several days after the power supply was discontinued. No decrease of magnetic induction was observed during that time. The system withstood the rigors of transportation and effects of high-explosive detonation.

The VG-5 explosive generator was a spin-off of the IVT's comprehensive program to develop high-power MHD generators, such as the U-02 and U-25. It was the direct result of research begun at the institute in 1962 to develop superconducting magnets for MHD generators. The IVT was joined in this effort by the Central Research Institute of Ferrous Metallurgy and the All-Union Research Institute of the Cable Industry.

The construction of and experiments involving the VG-5 generator were essentially a feasibility study to determine the practicality of a pulsed MHD generator with an independent superconducting magnetic system. The authors of the study concluded that such a system was indeed practical [43,113,114,115].

C. MHD SYSTEMS DRIVEN BY NUCLEAR ENERGY

In the conception of future energy technologies based on fusion (or thermonuclear) and fission reactions, the Kurchatov Institute of Atomic Energy is again the leading exponent and nucleus of activity, assisted by the Institute of High Temperatures in the area of MHD applications.

1. Thermonuclear Systems

Velikhov, with Golubev and Chernukha, published a paper in 1974 sketching two variants of an explosive MHD generator for thermonuclear power plants capable of delivering 10^{11} J at 10 GW per pulse [116]. Velikhov's concept is, of course, far beyond the state of the art and, as presented, was too superficial to be considered on its technological merits. Nevertheless, some aspects of the idea are worth examining from the point of view of pulsed power. First, the explosive MHD generator seems to be more suitable as a source of very high current pulses than as a commercial electric power generator, its ostensible purpose. Second, Velikhov's follow-on paper developing this idea indicates that a substantial amount of work has already been done, leading to the conclusion that the concept may be something more than futuristic speculation.

One variant of Velikhov's generator is an induction-type MHD machine [117], employing a massive sodium slug traveling in a pipe between two spherical detonation chambers alternately firing thermonuclear charges. The pipe passes through a solenoid connected to the load. The efficiency of converting the energy of the thermonuclear explosion into electrical energy depends on the efficiency with which the slug is accelerated by the explosion and decelerated in the

magnetic field. After the slug is accelerated, the metal vapor is condensed by the injection of liquid metal. The following are the design parameters of the projected inductive MHD generator:

Average electric power	5 GW
Energy per pulse	70 GJ
Interval between firings	12 sec
Detonation chamber	
Maximum pressure	1 kbar
Maximum temperature	1.1 eV
Volume	300 m^3
Slug	
Minimum velocity	30 m/sec
Maximum velocity	100 m/sec
Mass	16 kton
Acceleration efficiency	0.7
Solenoid	
Field	4.5 tesla
Field energy	10^{12} J
Field length	65 m
Field diameter	13 m
Compression ratio	200
Joule losses	0.1
Total system efficiency	0.6

The other variant is the conductive MHD generator, a supersonic system with continuous electrodes, in which the explosive thermonuclear charge is surrounded by a lithium blanket. Lithium vapor is the working fluid of the MHD cycle, and the system operates with equilibrium plasma. The following are the design parameters of this projected system:

Average electric power per pulse	10 GW
Maximum power	25 GW
Energy per pulse	100 GJ
Detonation Chamber	
Maximum pressure	1 kbar
Maximum temperature	1 eV
Minimum temperature	0.35 eV
Radius	4.5 m
Outflow time	4.5 sec
MHD channel	
Overall length	7 m
Stagnation length	2 m
Critical cross section	0.35 m^2

Outlet cross section	$2\ m^2$
Magnetic Reynolds number	0.4
Inlet Mach number	
Maximum	4
Minimum	2
Maximum induction	1.2 tesla
Output current density	$10^2\ A/cm^2$
Electric field intensity	10^2 V/cm
Efficiencies	
Plasma enthalpy extraction	0.8
MHD conversion	0.5
Total	0.4

The fact that this is a pulsed system, of course, creates problems of compatibility with the normal operation of an electric power plant. The primary means of compensation is the time-variation of the magnetic field designed to match the variable plasma parameters with the optimum conditions of MHD energy conversion. The principal problem of this system, however, is that utilization of the plasma thermal energy is incomplete because of the evacuation of the detonation chamber before each shot. To overcome this problem, Velikhov introduced a stationary plasma source into the thermonuclear reactor system [118], a modification previously suggested by Williams and Clement which promises the high efficiency of 0.7.

Velikhov considered the technical problems associated with the design of such highly efficient Faraday MHD generators for 10-GW thermonuclear power plants, in particular, factors controlling efficiency: MHD channel flow, properties of the working fluid, separation of the boundary layer, plasma flow stability, and changes in input parameters of the MHD channel caused by the evacuation of the plasma source. In the case of the stationary plasma source, the working fluids are water, argon, and helium seeded with potassium or lithium. Velikhov assumed the following initial parameters for his system:

Thermal power of the plasma source	20 GW
Stagnation pressure	500 bar
Stagnation temperature	1 to 2 eV
Load factor	0.85

The effect of stagnation temperature, Mach number, magnetic field intensity, and seeding ratio on efficiency was determined for each working fluid. Table 2 shows Velikhov's calculations for MHD generators using the above working media. For water vapor, regime I corresponds to isenthalpic flow and unseparated stagnation up to M = 1.2; regime II occurs when the condition of stability of the boundary layer is selected as the driving function at the point of separation. The effect of evacuation of the closed plasma source on the MHD channel input parameters was investigated using the lithium vapor variant of the MHD generator. The energy conversion efficiency was 25 percent. This is lower than the 40 percent efficiency given in Velikhov's first paper and the difference is attributed to a disruption of the effective flow stagnation.

Table 2

MHD GENERATOR PARAMETERS

Working Fluid Parameter	Water + 5% K			Argon + 0.5% K		Helium + 3% K		Lithium	
		Output							
	Input	Regime I	Regime II	Input	Output	Input	Output	Input	Output
Mass flow rate, kg/sec	300			2000				250	
Relaxation temperature, K	12,000			15,000		23,000		13,200	
Mach number	4.30	1.20	1.20	3.30	1.20	4.41	1.20	4.20	2.57
Pressure, bar	1.54	0.23	0.057	8.9	2.2	2.87	0.20	3.0	0.35
Temperature, K	4060	3610	3250	4090	4080	3590	3520	3610	3030
Effective conductivity, mho/m	540	420	280	610	445	395	470	49	22.5
Hall factor	0.13	0.56	0.76	0.44	1.07	0.18	0.76	0.06	0.25
Magnetic field, tesla	0.35	0.27	0.11	1.28	1.05	0.56	0.30	1.90	0.97
Channel cross section, meters	0.91 x 0.91	4.40 x 4.40	5.90 x 5.90	0.70 x 0.70	2.36 x 2.36	0.49 x 0.49	3.60 x 3.60	0.58 x 0.58	2.07 x 2.07
Channel length, meters		21	21	15.0		15.8		8.0	
Voltage, kV		2.5	2.5	3.0		3.2		10.0	
Electric power, GW		12.2	11.3	13.8		14.2		10.2	
Power conversion coefficient, %		55.2	51.0	69.2		81.9		44.7	

The generator wall can be cooled and protected by transpiration. However, pressurized blowing of cooling agents through the wall promotes the separation of the boundary layer. On the other hand, the flow stagnation without separation calls for negative pressure at the wall in the boundary layer region. These conflicting requirements can be resolved by using a modular wall, each module to be cooled by transpiration and a portion of the working fluid to be

bled off through gaps between the modules and cooled. Calculations show that a circular-transpiration helium supply, with a subsequent cooling of the bled-off gas, can remove heat at the rate of 10 kW/cm^2 and can maintain a stable boundary layer. Promising materials for the modular walls of the MHD channel at 2000 K are porous molybdenum or tungsten filament structures or filament crystals of aluminum oxide or boron nitride.

Velikhov said at that time that MHD generator prototypes up to 1 GW were ready to be tested; problems requiring a stabilized flow could be investigated in stationary plasmatrons and other problems could be studied in large shock tubes [116,117].

2. Fission Systems

V. A. Dmitriyevskiy of the Kurchatov Institute and L. A. Zaklyazminskiy of the Institute of High Temperatures in 1971 jointly proposed an induction-type MHD generator coupled to a nuclear reactor [118]. This idea had originally been advanced by Colgate and Aamodt in the United States in 1957. Although the Soviet proposal is fairly well known in the West, it may nevertheless be useful to recall its main points here. It is based on two considerations:

1. Any increase in efficiency over 50 percent is obtained solely from MHD conversion in the channel.
2. The channel wall temperature must be kept below 1000 K so that available materials can be used.

Because materials considerations impose a temperature limit of 1500 to 2000°C on the conduction-type MHD generator intended to operate with nuclear reactors, the advantages of MHD operation can be best realized by the induction-type generator with its high gas temperature. Such a system consists of a cavity nuclear reactor with fissioning gas, directly connected to a channel for the radial expansion of the gas.

Efficient MHD power generation requires a minimum peak gas temperature. In fact, even with seeding, significant equilibrium

conductivity of the gas can be obtained only above 2000°C. To satisfy the requirements of (1) realistic channel length, (2) output pressure of 1 atm, and (3) 50 percent of input gas enthalpy converted to electricity, the input gas temperature would have to be $\geq$ 4000 K. The working gas cannot be heated that high either by chemical fuel or by a solid-fuel nuclear reactor. The only heat source capable of achieving the requisite temperature with a constant high gas flow is a nuclear reactor with fissioning gas, in which a large quantity of heat is delivered to the working gas away from the solid walls. In an induction MHD generator, the wall of the reactor and the MHD channel can be cooled with liquid or gas. This cooling method requires that the MHD channel be short and close to the reactor.

Efficient MHD power generation also requires an MHD channel that can accommodate a large gas expansion ratio. The energy from an MHD induction generation can be delivered to the load only in the case of nonstationary interaction of the working gas with the magnetic field. The currents flowing in the working gas of an induction system form a closed loop within the gas. Therefore, only a vortex electric field due to the time-variable magnetic field can exist within the gas. The nonstationary condition can be imposed on either the gas flow or the magnetic field. The gas velocity in the channel should also be perpendicular to the magnetic field. Therefore, a wide, short channel and high magnetic Reynolds numbers require that the gas flow be nonstationary (see Fig. 13).

The fission gas expands radially in the MHD channel and normally to the magnetic field, causing oscillations of the magnetic field intensity. The output current winding reacts to the deformations of the magnetic field caused by the gas. The spent gas is cooled in the heat exchanger, separated into the initial components, compressed and returned to the reactor. The heat from the exchanger can be utilized in a conventional steam cycle.

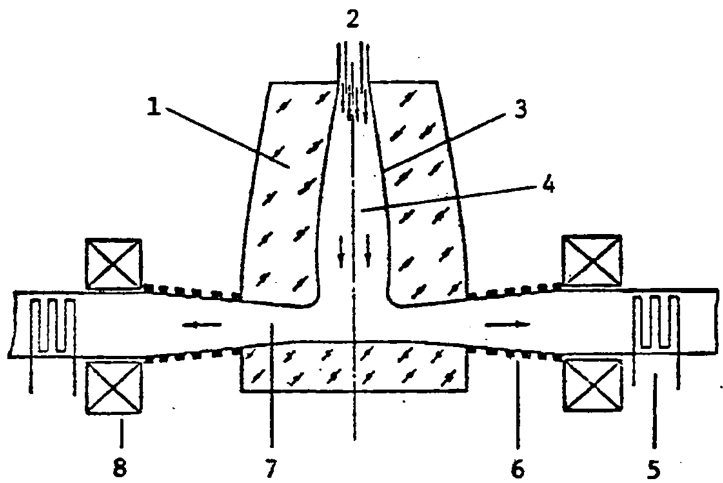

Fig. 13--MHD induction generator for use with nuclear reactor [118]

1--Moderator and reflector
2--Fissioning gas
3--Transpiration cooling gas
4--Reactor cavity
5--Heat exchanger
6--Output current winding
7--MHD channel
8--Excitation winding (constant magnetic field)

The optimum frequency of the output current circuit is 500 Hz, although it could in principle be 50 Hz. The minimum inlet radius is 0.5 m. The average MHD channel width is 0.5 m and length, 3 m. The mean gas velocity in the channel is 500 m/sec. Total channel outlet pressure is 1.1 to 1.2 atm, total inlet pressure is 35 to 40 atm, magnetic field intensity is 20 to 25 kG. The output power of the system then is 500 MW. The conclusions reached from a preliminary analysis are (1) that the system will be effective only at power levels of 500 MW where the overall system efficiency reaches 60 percent and (2) that the system will yield a high energy output per unit weight of the working gas and per unit volume of the power plant.

The high compression of large quantities of gas requires a Rankine cycle. The fissionable material additive can be metallic

uranium, plutonium, or their compounds. The use of uranium hexafluoride, because it will eliminate the need to maintain high wall temperatures to avoid condensation, will simplify the construction of the primary loop. Despite its disadvantages, uranium hexafluoride should be the first candidate material for the prototype system. Since the properties of UF_6 at high temperatures are not well known, A. I. Baz' and V. P. Sapozhnikov attempted in 1966 to calculate its equation of state. Within the same project, V. A. Dmitriyevskiy studied the properties of UF_6 at high temperature in a pulsed nuclear reactor with a dense neutron flux. The external moderator can be heavy water, beryllium, or graphite. Calculations show that a fission chain reaction can be achieved in a cavity with a 50-cm radius in which the critical mass is 4 kg for U^{235} or 5.9 kg for UF_6.

The design of the system can profit from the utilization of the T-layer phenomenon reported earlier by the team working on this project. The T-layer is a high-temperature, self-maintaining layer of gas arising under certain conditions in an electrically conductive gas expanding in a magnetic field. The T-layer can be artificially induced by injecting an electric conductivity perturbation into a stationary gas flow. The T-layer will increase the magnetic Reynolds number by one or two orders of magnitude.

IX. HIGH-CURRENT OPENING SWITCHES FOR INDUCTIVE STORAGE SYSTEMS

The Soviets' comprehensive approach to research and development of pulsed-power systems is evident also in their treatment of the key component of inductive storage systems, i.e., the high-current switch. Theoretical and experimental investigation of the broad range of problems encountered in the design of satisfactory opening switches for kiloampere and megampere currents has been pursued at the Yefremov and Polytechnic institutes in Leningrad and the Automation and Electrometry, Nuclear Physics, and Hydrodynamics institutes in Novosibirsk. An account of the main lines of research in this area follows.

A. INDUCTIVE STORAGE SWITCH THEORY

A research team at the Institute of Automation and Electrometry in Novosibirsk was responsible for a basic analysis of inductive storage circuits. The key members of the team headed by Yu. Ye. Nesterikhin, director of the institute, are L. S. Gerasimov, V. I. Ikryannikov, and A. I. Pinchuk [119,120]. The analysis postulates several idealized switch-load conditions: (1) resistive switch, inductive load; (2) resistive-inductive switch, inductive load; (3) resistive switch, resistive load. Criteria for effective energy transfer are developed for each case.

1. Resistive Switch, Inductive Load

It is assumed that the inductive storage has been charged from an external source and energy is about to be transferred from storage to load. The end state of the system takes place after current has been interrupted in the R branch (see Fig. 14). The end state can be determined directly from the energy and magnetic field conservation laws, according to Maisonnier [121]. The switching process itself is considered from the viewpoint of surface vaporization waves generated in exploding waves, as developed by Bennet [122].

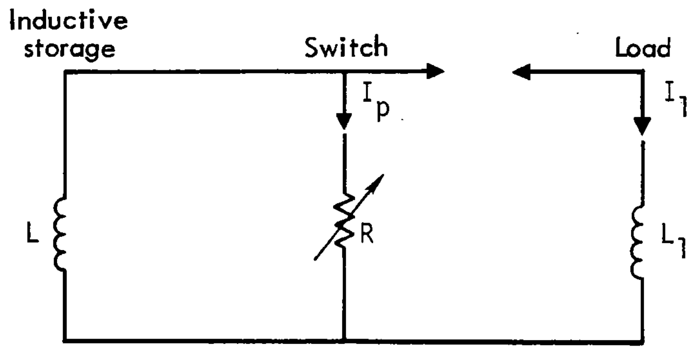

Fig. 14—Equivalent circuit of resistive switch and inductive load configuration

It is assumed that the peak resistance of the exploding wire occurs at the boiling point of the wire metal, at t = 0, $R = R_k$ (R_k is boiling point resistance), $I_1 = I_p = I_0$, and the spark gap closes at t = 0. The opening switch resistance R is

$$R = \frac{R_k}{1 - \dfrac{Q_p}{m_0 q}}$$

where Q_p is the Joule heat liberated in the wire after t = 0, m_0 is the initial mass of the wire, and q is the electric explosion energy per unit mass. The value of q is determined experimentally. The criterion of energy transfer is the quantity $L_e I_0^2/2m_0 q$, where $L_e = LL_1/L + L_1$ is the equivalent inductance of the circuit.

For low energies delivered to the switch: $L_e I_0^2/2m_0 q < 1$, there is no full vaporization of the wire, and the load current tends asymptotically towards the steady-state value. For high energies: $L_e I_0^2/2m_0 q > 1$, and R turns to infinity within a finite interval of explosion. However, the electric explosion fails to interrupt the current, inasmuch as overvoltage breaks down the gap formed by the exploding wire. This breakdown cannot be avoided without violating the conservation laws. The current in the discharge channel

continues to flow until the total energy absorbed in the R branch after $t = 0$ reaches a critical value. After that, the discharge ceases regardless of the resistance of its channel. The duration of the electric explosion is inversely proportional to $L_e I_0^2/2m_0 q$. For critical energies: $L_e I_0^2/2m_0 q = 1$, R turns to infinity in time $t = L_e/2R_k$, $I_p = 0$, and the electric explosion either occurs without breakdown, or the breakdown current is small and quickly quenched.

The applicability of this model depends on the velocity of the surface vaporization wave v and the criterion of energy transfer $L_e I^2/2m_0 q$. The time t decreases as the criterion of energy transfer increases. This model is not applicable when the latter is so high that $t < \ell/v$, where ℓ is the radius of the exploding wire. According to Webb [123], v does not exceed 200 m/sec, so that for $\ell < 0.1$ mm, t should be of the order of 10 to 100 μsec, as observed by Bennet and Early [122,124].

2. Resistive-Inductive Switch, Inductive Load

Here, although the portion of energy transferred from the inductive storage to the load is the same as in case 1 above, the current interruption process differs: In addition to the energy lost in the resistance, that stored in the parasitic inductance is totally absorbed (see Fig. 15). Consequently, the efficiency of the inductive switch is lower. The criterion of energy transfer is the same as in case 1.

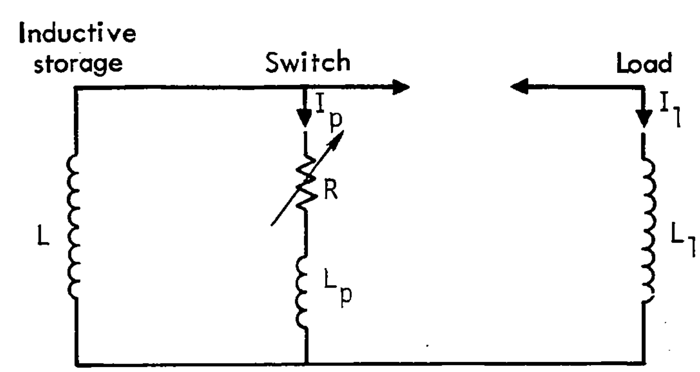

Fig. 15--Equivalent circuit of resistive-inductive switch and inductive load configuration

3. Resistive Switch, Resistive Load

There are basic differences in the way energy is transferred to inductive and to resistive loads. For inductive loads: the current in the switch or load branch determines the portion of the energy transmitted to the load and the portion remaining in storage. For the case of complete switch opening, the energy transferred to the load is determined only by the initial conditions and does not depend on whether electrical or chemical explosion is used. For resistive loads: the energy Q_1 transferred to the load no longer depends on I_1 alone, but is determined by the integral $\int_0^t R_1 I_1^2(t)dt$, i.e., it depends on the switching process, as well as on the initial conditions (see Fig. 16). For example, if the switch were assumed to open instantaneously, all the stored energy would be delivered to the load, because as $t \to 0$, the energy absorbed by the switch $Q_p \to 0$.

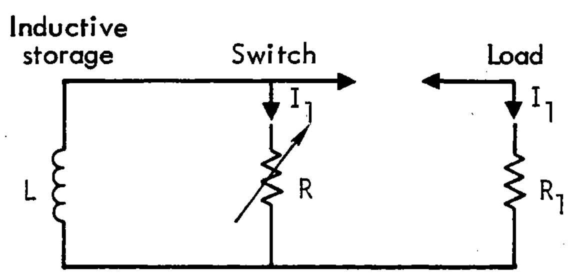

Fig. 16--Equivalent circuit of resistive switch and resistive load configuration

The switch resistance R is in this case also considered from the viewpoint of the surface vaporization wave model. For any resistive load, the final resistance of the switch never becomes infinite, i.e., there is no true electric explosion and the switch wire is never completely vaporized. The limiting value of the switch resistance depends on load resistance and is a function of the energy transfer criterion $L_e I_0^2/2m_0q$. As in the case of inductive

load, at low energies there is no significant rise in R and no effective energy transfer. At high energies, where $L_e I_0^2/2m_0 q \geq 2$, switch resistance, although still finite, is very high if the load resistance is high, or at least higher than the boiling point resistance R_k of the switch wire.

The voltage, always low at low energies, is theoretically unlimited at high energies. With increasing input energy and low load resistance, the energy delivered to the load increases faster than the load power. At high load resistance, the reverse is true. The total efficiency of the system can approach unity for $L_e I_0^2/2m_0 q$ >> 1, when the energy of the electric explosion of the switch is much lower than the stored energy. However, within the practical range of load resistances, the total system efficiency cannot exceed 30 percent. In the case of purely inductive load, the maximum efficiency is 25 percent.

The case of the high-current explosive switch in a system consisting of an explosive magnetic flux compression device as the energy source and a single-turn coil as the inductive load was also analyzed [125]. The electrical leads connecting the flux compression device to the switch and load served as the inductive energy storage component. The system operates in two stages: Stage 1 is the compression of the magnetic flux and heating of the switch metal to the boiling point; stage 2 is the explosive vaporization of the switch metal and interruption of current in the switch. During the process of compression of the magnetic flux, the load is disconnected and energy is accumulated in the inductive store. The electric explosion of the switch occurs at the end of the flux compression. The voltage pulse resulting from the sharp increase in the switch resistance breaks down the spark gap and energy is delivered to the load. This model of the system also assumes zero resistance of the flux compression device, leads, and load, and zero inductance of the switch. Also assumed are constant-width rails of the flux compression device.

The system essentially resembles the case of resistive switch, inductive load presented above, with the addition of the variable

L_s of the energy source. The aim of the analysis was to match the parameters of the flux compression device to those of the switch in order to explode the switch metal at the time when $R(T) = R_k$ (Fig. 17). The switch metal under consideration was Al and Cu.

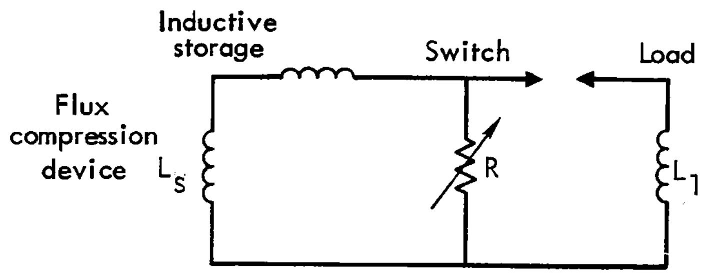

Fig. 17--Equivalent circuit of the flux-compression device driving a load

The match depended on the relationships among the following parameters:

$$\tau_0 = \frac{L_0}{R_0 T}, \qquad b = \frac{\beta I_s^2 L_s}{2m_0}, \qquad \eta = \frac{L_s}{L},$$

where $L_0 = L_s(0) + L$, $R = R$ at $t = 0$, $T = t$ when $R = R_k$, and β is the ratio of the thermal coefficient of resistivity to the specific heat capacity of the metal. For sufficiently large τ_0 and fixed η, b was a linear function of τ_0. The operating range of τ_0 values was 30 to 130 for Cu and 30 to 100 for Al; b ranged from 0.5 to 13. Furthermore, it was found that if $\eta L_1 >> 10\ R_0 T$, the load current during stage 1 was low enough to permit the elimination of the spark gap, so that the load coil was connected directly across the switch.

B. HIGH-CURRENT SWITCH DESIGNS

The designing and testing of high-current switches for inductive storage devices has occupied a sizable number of personnel at the Yefremov Institute, where at least 40 authors have been active in

this field during the last two years. O. A. Gusev, deputy director for research of the Yefremov Institute, has participated directly in this effort. The key members of the team researching opening switches are A. M. Stolov, F. M. Spevakova, and V. G. Kuchinskiy. The bulk of published material reflecting the Yefremov Institute switching research did not appear in the regular serials, but was released as proceedings of the 1974 Joint U.S.-USSR Seminar on Systems Analysis and Construction of Thermonuclear Power Plants. However, none of the technical reports in the proceedings or in other sources specifies fusion work as the particular application of the inductive storage systems. Rather, conforming to the usual Soviet practice, these reports offer vague and general statements of purpose, for example, that the utilization of inductive energy stores requires fast-acting switches capable of handling energies of 10^5 to 10^7 J and currents of several hundred kA [126] or of switching quasi-dc circuits of MA currents at extremely high power [127].

The following institutes (in addition to the Yefremov) and researchers were active in the development of high-performance opening switches:

Institute of Hydrodynamics: Ye. I. Bichenkov and V. A. Lobanov

Kurchatov Institute of Atomic Energy: Ye. A. Azizov and N. A. Akhmerov

Institute of Mechanics, Moscow State University: K. I. Kozorezov and V. V. Semchenko

Leningrad Polytechnic Institute: A. A. Drozdov, B. V. Yefimov, and Yu. P. Kubar'kov

Institute of Atmospheric Optics: G. A. Mesyats and B. M. Koval'chuk

Unidentified facility: V. G. Artyukh and S. A. Smirnov

Table 3 compares the basic operating parameters of U.S. and Soviet opening switches. Soviet opening switches are discussed in greater detail in the following subsections.

Table 3

HIGH-CURRENT OPENING SWITCHES

	I,kA	V,kV	Delay Time	Store Inductance	Remarks	Developer	Date	Ref.
Soviet Designs								
Chemical-HE disrupting conductor	35	8	2 μsec	430 nH	Single-shot	HYD	1974	129
Chemical-HE disrupting conductor	100	--	5 μsec	--	Single-shot	HYD	1975	130
Chemical-HE disrupting conductor	100	50	100 μsec	--	Single-shot	KUR	1974	131
Chemical-HE disrupting conductor	50	10	15 μsec	100 μH	Single-shot	MGU	1974	132
Magnetic-field disrupting conductor	40	6	200 μsec	--	Single-shot	YEF	1974	139
Exploding-foil driving paraffin	500	25	50 μsec	6 μH	Single-shot	YEF	1974	127
Exploding-foil driving paraffin	50	30	100 μsec	320 μH	High efficiency	YEF	1974	135
Pneumatic piston drive	50	40	1 msec	--	Repetitive	YEF	1974	139
Nonlinear resistance	200	20	100 μsec	--	1 min reset	YEF	1974	137
Gas-discharge tube shunt	100	50	25 μsec	--	Repetitive	YEF	1974	146
Field-emission diode	35	6,000	10 nsec	--	Repetitive	LPI-YEF	1976	141
Field-emission diode, projected	500	10,000	--	--	Repetitive	LPI-YEF	1976	141
Gas-discharge controlled by electron beam, proposed	150	--	200 nsec	--	Repetitive	IAO	1976	134
Mechanical sliding plates	12	--	10 μsec	--	Repetitive	--	1975	147
U. S. Designs								
Vacuum arc	10	25	2 μsec		1 kHz rep rate	SUNY	1976	160
Vacuum arc, projected	50	100	1 μsec		10 kHz rep rate	SUNY	1976	160
Exploding foil	6	100	500 μsec		--	NRL	1976	160
Wax-filled exploding foil	50	17	20 μsec		--	NRL	1976	160
Electron-beam controlled	25	50	100 nsec		--	Maxwell	1976	160
Electron-beam, projected	1000	50	--		--	Maxwell	1976	160
Plasma erosion	75	2,500	5 nsec		--	Sandia	1976	160

1. Switches Employing Chemical High Explosives

Scientists of the Nuclear Physics Institute in Novosibirsk consider the most urgent switching problem to be that of interrupting current for periods ranging from a few to tens of microseconds in circuits containing large inductances [128]. In their judgment, the electric explosion of wires and foils is not a satisfactory solution to the problem, inasmuch as this method is not readily controlled, particularly in circuits with long periods of current flow. The Soviets contend that, in such cases, chemical high explosives offer a better alternative, despite the fact that their use precludes repetitive action, and have gone on to develop a large array of switches incorporating chemical high explosives as the driving element. The main developers of this type of opening switches are the Nuclear Physics and Hydrodynamics institutes, both in Novosibirsk.

The Bichenkov-Voytenko team responsible for the development of explosive flux compression generators at these institutes has also developed several designs of inductive storage opening switches utilizing chemical high explosives [128,129,130]. The switches operate in the 30 to 100 kA range. The chemical high-explosive method was chosen over electrically exploding wires or foils as affording more control of the process of current interruption and compatibility with long-pulse circuits.

The initial design was based on three stages of switch operation: (1) establishment of an electric arc across a break in the circuit; (2) quenching of the arc by gas flow; and (3) filling of the high-field intensity region with material having a sufficiently high electrical resistance. The team claims the following advantages for the condensed high explosive over the conventional methods:

1. Fraction of a μsec accuracy in switch synchronization by external command.
2. High velocity (>1 km/sec) of break formation and influx of detonation products whose electric resistance exceeds that of air.

3. Arc quenching several orders faster than that achieved by conventional methods. The quenching flow of detonation products is characterized by high density (1 g/cm^3) and low temperature (an order lower than the arc plasma temperature).

Switch operation is as follows [128]. The arc is originally established between two needle electrodes by an electrical discharge, and allowed to develop. The HE cartridge is placed at right angles to the arc axis. Upon detonation, a shock wave formed at the detonation front moves toward the arc axis, accelerates the arc, and removes it from the interelectrode gap. In the initial stage of this process, the wave front is the boundary of the conductive region of the arc channel. The arc intensity decreases and electromagnetic forces detach it from the wave front. At this point, the arc is cooled intensively by gas moving ahead of the detonation products. Later, the conducting arc channel comes in contact with the dense detonation products, which are colder than the arc plasma. This contact leads to a more intense cooling and quenching of the arc. At this time, the interelectrode gap is filled with the detonation products of high electrical resistance, preventing further breakdown. The measurements of the density of the detonation products, the arc current, and the arc blow-off time were as follows:

Density (g/cm^3)	Arc Current (kA)	Arc Blow-off Time (μsec)
0.9	0.5	2.1
	1.6	39
1.1	0.7	2.2
	2.0	23
1.3	0.8	2.4
	2.5	15

In subsequent experiments, the arc was extinguished in gaps created by the high explosive. The detonation was set off deliberately

at the most undesirable time, when the current reached its peak value. The switching times obtained in the experiment were as follows:

HE Weight (g)	Peak Current (kA)	Circuit Capaci-tance (μF)	Circuit Inductance (μH)	Rail Cross Section (mm^2)	Switching Time (μsec)
100	50	300	~5	50	15 to 50
25	6.5	300	~30	1000	10 to 40
40	10	300	~125	2000	15 to 50

The detonation product velocity in the experiments ranged from 3 to 5 km/sec; the gaps were established at the velocity of 2 km/sec.

The program of further investigation called for the following measures:

1. Accelerated formation of gaps obtained by sophisticated hydrodynamic techniques (shaped charges, natural and artificial sequencing of gaps).
2. Forced interaction (by shaped charges) between the detonation products and the arc. (The problem here is that this could sharply decrease the electrical resistivity of the detonation products.)
3. Plotting the volt-second characteristics of the detonation products in various stages of expansion.
4. Considering secondary breakdowns due to the motion of shock waves in the magnetic field of the current and in the electric field induced by the current interruption. This requires the study of the electric resistance of air compressed by the shock wave.
5. Plotting the distribution of electric conductivity of the detonation products.

The team subsequently attempted to simplify the problem by redesigning the switch configuration to eliminate the arc stage altogether [129]. In this design, the electrical arc could not be

formed in the air surrounding the break in the metal conductor. It could arise only in the more dense detonation products where it was readily quenched.

Two design variants were used. The first featured a 0.05-mm copper strip 20 mm wide on a Plexiglas substrate as the conductor. The conductor supported a 50/50 trotyl-hexogen charge with an HE plane-wave lens. With this design, the typical switching time down to 30 percent of the 35 kA peak current was 2 μsec. The current inductance was 430 nH and the voltage at current cutoff, $v = L\,dI/dt$ = 8 kV, which was 8 times the capacitor bank voltage. The switch resistance increased by a factor of 100, reaching 0.1 ohm.

The second variant featured a cylinder of 0.007-mm aluminum foil wound around two copper disks serving as the electrodes. The same 50/50 trotyl-hexogen charge was placed inside the cylinder between the disks, and an additional plastic explosive was inserted between the windings of the foil. The explosive was set off on the axis of the cylinder, and the expanding detonation wave disrupted the entire foil surface. The switching time of 2 μsec and the time behavior of the current were the same as in the first variant.

Bichenkov has also built a sophisticated explosive opening switch for a system comprising an explosive flux compression device and a single-turn coil [130]. A similar system, considered theoretically by Gerasimov [125], was discussed above. However, Gerasimov's analysis was based on the need to match the parameters of the exploding wire to those of the flux compression device. Since Bichenkov used a chemical high explosive in the switch, his theoretical approach was different. Bichenkov considered the efficiency of the energy transfer from the inductive storage to the load, which depends on load resistance and the ratio of storage and load inductances. Low-inductance stores work well only with low-inductance loads, while high currents flowing through highly resistive loads produce excessive voltages. These considerations impede the broad application of explosive flux compression devices.

Bichenkov offered a solution to this problem based on an explosive flux compression device with a variable storage inductance. This was

accomplished by building an inductive store with N turns connected in parallel which could be switched to a series configuration. Thus, the store inductance was initially low and the store was well matched to the flux compressor during the energy accumulation stage. When switched in series, the current in the store decreased N times and the inductance increased N^2 times. Consequently, the series-connected store could be matched to almost any load.

The object of Bichenkov's experimental investigation was a switch designed to handle current densities of 500 kA/cm, typical of bellows-type flux compressor output. The switch was to be relatively small and easily controlled. Bichenkov's main switching element is shown in Fig. 18. The notches in the switch ring facilitate its breakup during detonation. A high-explosive charge 5-mm thick was placed inside the ring.

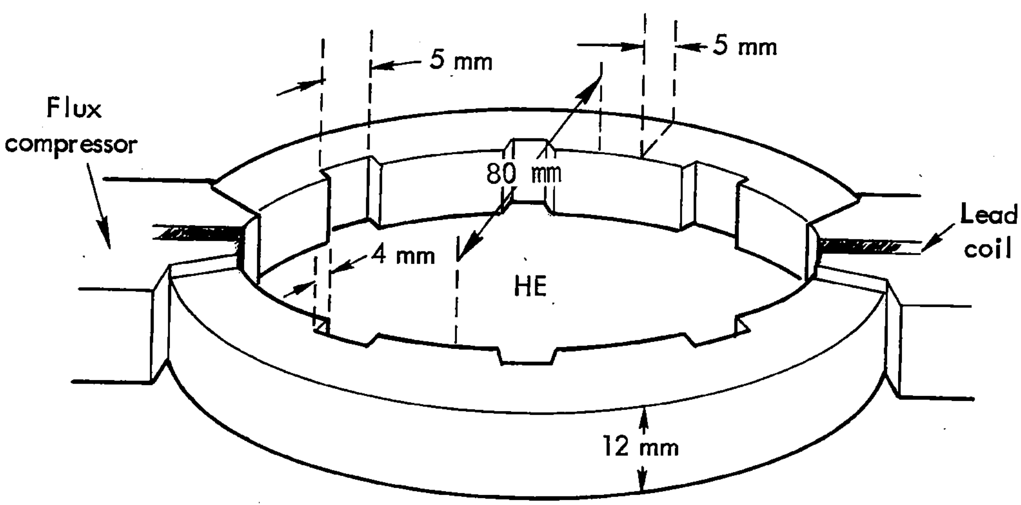

Fig. 18—Opening switch for the variable-inductance storage system

The energy Q_s lost in the switch is

$$Q_s = Q \frac{L_s}{L_s + L_1} ,$$

where Q is the energy delivered from the source to the switch, L_s is switch inductance, and L_l is load inductance. It is obvious that L_s should be as small as possible. To reduce L_s further, Bichenkov used metal side plates to partially displace the magnetic field from the ring interior.

The actual experiments with the switch employed a 10-mF, 5-kV capacitor bank as the energy source instead of the flux compression device. The high-explosive charge, set off at peak current, first shunted out the capacitor bank and then opened the coil circuit. Uncontrolled interruption of the 400-kA current was found to occur within an interval of 18 to 25 μsec. Bichenkov admitted the possibility of premature detonation in this case caused by the magnetic pressure's (300 kgauss, 4×10^3 atm) rupturing one of the ring notches and producing an arc. For 100 kA, the switch operated normally within 5 μsec. Doubling the current increased switching time to 50 μsec.

Further experiments were performed with 3-mm side plates reinforcing the notches outside the ring to prevent rupture by the magnetic field. As an additional measure against high-current arcing, an auxiliary high-explosive was set off ahead of the main detonation to create a highly resistive atmosphere near the notches. Under these conditions, it was possible to interrupt a current of 300 kA in 5 μsec. Bichenkov considered these results as an adequate proof of the feasibility of explosive magnetic flux compression generators for variable-inductance storage systems.

Opening switches utilizing HE were also designed by the Kurchatov Institute in cooperation with the Institute of Mechanics of the Moscow State University. A two-stage switch for an inductive storage system consisted of a hollow cylinder filled with dielectric and disrupted by a high-explosive charge as the first stage. The second stage was one or several exploding wires housed in a mechanically strong insulator. The following optimum parameters were obtained [131]:

Switchable current	100 kA
Voltage	50 kV
Duration of current flow	100 μsec
Stored energy	20 MJ

The research focused on obtaining shorter pulses, between 10 and 100 μsec. Several designs of switches with tubular conductors were considered. For currents within the range of 0.75 to 53 kA, the first stage of the switching process, depending mainly on design factors, was easily reproducible. Subsequent stages for voltages > 3.5 kV were found to depend on the nature of the load. The first stage developed a power of 10^8 W in 10 to 20 μsec [132].

Experiments were recently carried out at the Kurchatov Institute to test the effect of various dielectric materials on the operating time of circuit breakers employing chemical high explosives to disrupt the conducting element [133]. The switch configuration tested, similar to the first stage described above, consisted of a column of HE inside a tubular conducting element, all enclosed in a cylindrical switch housing. The space between the conductor and the housing was filled with the dielectric under investigation. The behavior of the dielectric during the explosive expansion of the hollow conductor determines the antiarcing properites of the switch, as well as the current switching rate and the speed of restoration of electric strength of the switch.

The switch was tested in an inductive storage circuit driven by a 200-kJ capacitor bank. The peak current was 25 kA, and the open switch voltage reached 55 kV. Experiments with divers dielectric fillers gave the following results for the time from the detonating pulse to the observed deformation of the shell, the velocity of the fragments, the maximum rate of change of arc resistance, and the rate of change of voltage:

Dielectric	t_0 (μsec)	$\Delta v/\Delta t$ (m/sec)	$\Delta R/\Delta t$ (Ω/sec)	$\Delta V/\Delta t$ (V/μsec)
Air	22.4	425	610	--
Paraffin	25.2	335	733	1557
Vaseline	22.6	351	1100	1518
Oil	21.7	388	1025	1487
Water	19.6	325	--	--
Ground teflon	37.2	405	616	1470
Quartz sand	35.7	510	460	700

2. Switches Using Electric or Magnetic Field to Disrupt Conductors

A bundle of exploding micron wires is regarded as the only switching device capable of producing high-power nanosecond pulses in inductive storage systems [134]. However, like the HE-driven switch, this is a single-shot device with a limited range of applications. The exploding wire or foil and the conducting element collapsed by a magnetic field pulse are usually components of a complex switching system designed to handle high pulsed powers. The voltage gain obtainable currently with exploding-wire switches does not exceed 4 to 6. The power can be increased by resorting to the multistage configuration, although special measures must be taken to maintain adequate efficiency [135].

A team headed by F. M. Spevakova and A. M. Stolov at the Yefremov Institute specializes in single-stage multigap switches and multistage switches with nonlinear thermal shunt resistors. A single crystal of tungsten is an example of a thermal shunt with an optimal temperature range [136,137].

One form of the multistage nonarcing switch is based on the introduction of reverse current establishing a net zero current in the main switch. A choke coil charged by an auxiliary capacitor provides the reverse current. The duration of the zero-current interval depends on the energy stored in the auxiliary capacitor. The electrodynamic drive element incorporated in the switch, by reducing the duration of the zero-current interval to 200 μsec, acts fast enough to keep the auxiliary capacitor small. The jitter is low enough (10 μsec) to allow for the synchronization of a number of switches. The design of the electrodynamic element is based on the destruction of a light metal cylinder, serving as a contactor, by a pulsed magnetic field. This design has been tested in interrupting currents of 40 kA at 6 kV and 20 kV [138,139].

An alternative approach to the design of high-current switches provides for a single-stage operation and a number of circuit-breaking gaps that can be opened consecutively or simultaneously. Each gap employs exploding foil and is replaceable. The Yefremov Institute has been developing and testing several versions of this switch.

The design principle calls for (1) the separation of the explosion products from the insulating medium, such as paraffin, injected into the gaps, (2) the use of the explosion products to extinguish arcing, and (3) the localization of the electric explosion within a small volume [140].

A recently reported [135] switch of this type, designed for operation in inductive storage circuits, delivers 10^8 to 10^9 W to the load at 30 kV, 50 kA. The total switching time does not exceed 100 μsec and the current rise time in the inductor is 10^{-3} to 10^{-2} sec. For 300 kJ of stored energy, the inductor delivers not less than 30 percent to a 1-ohm resistive load. With no-load operation, the voltage gain at the switch is 20 (second-stage voltage divided by the capacitor bank charging voltage).

The design of the switch provides for two stages connected in parallel. The first stage consists of ten parallel cells housing rolled aluminum tape separated by paraffin. An exploding short section of the tape propels the paraffin, which ruptures the rest of the tape and fills the break, ensuring an adequate electric strength of the first stage. The second stage is the usual exploding wire set in quartz sand. The current is switched to the second stage by a spark gap in a solid dielectric.

The theoretical analysis of various methods of reducing the power handled by opening switches while ensuring an adequate energy transfer to the load focused on nonlinear resistor shunts capable of varying their resistance during the switching process. According to the theory for a heated shunt resistor, a change in resistance by a factor of 50 decreases the switched power several times for the same power delivered to the load. Thermal shunt resistors can effectively replace the exploding wire or foil elements constituting the last stage of the multistage switch.

A model of a low-inductance, low-carbon steel resistor has been developed for an experimental investigation of nonlinear thermal shunt resistors. The model was cooled in liquid nitrogen and then heated in operation up to 800°C. Switching 200 kA in the resistor releases an energy of 160 to 180 kJ in 10^{-4} sec. The resistance

changes by a factor of 70 at a maximum voltage of 20 kV. The initial value of the resistor is about 5 percent of the load resistance. The resistor, a strip 15 mm^2 in cross section, has a specific energy capacity of 400 kJ/kg. The time required for the initial cooling is 15 min and for repetitive cooling after the passage of a current pulse, 1 min. The design provides for nitrogen leakage prevention and keeping the pressure within safe limits. The principal advantages of the variable resistor over exploding wires used with inductive storage devices are repetitive usage, high efficiency, and speed.

A single crystal of tungsten was studied as a candidate material for nonlinear resistors with a temperature range beginning with that of liquid helium. The experiments were performed with single-crystal tungsten wire 0.3075 mm in diameter and 1 m long. The results showed that the resistivity of the wire differed only slightly between the dynamic and static modes of operation. It was concluded that large specimens of nonlinear tungsten resistors are suitable for use in inductive storage devices [136,137].

3. The Electron Beam As the Switching Element

A number of interesting switch systems employing a high-current electron beam as the active element have been designed. These appear to be intended for special high-performance purposes.

G. A. Mesyats of the Institute of Atmospheric Optics proposed a fast nanosecond opening switch for inductive storage systems to handle currents above 100 kA and permit repetitive operation [134]. The switch, called an injection thyratron, consists of a gas-filled cavity in which a nonself-sustaining discharge is maintained by an electron beam. The current is interrupted by cutting off the electron beam. According to Mesyats's calculations, the characteristic time interval, t_0, following the beam cut-off can be as short as 70 nsec; the interval is defined as the time during which the electron concentration in plasma decreases by a factor of 10.

Mesyats performed verification experiments to measure t_θ under realistic conditions, using the gas-discharge cavity of a high-power

CO_2 laser for this purpose. The 300-liter cavity was filled with a CO_2:N_2:He = 1:1:3 mixture at atmospheric pressure. When a 15-kA electron beam (current density of 1.5 A/cm^2) was injected into the cavity and cut off after 2 μsec, a 150-kA current flowing through the cavity was interrupted in 200 nsec.

Mesyats concluded that the injection thyratron switch should operate best with compressed gas (p = 10 atm and over). This would decrease the current interruption time, since $t_0 \sim p^{-1/2}$, and increase the electric strength of the switch. For example, the switch with nitrogen subject to a μsec voltage pulse would have an electric strength of 60 kV/cm for p = 5 atm. Under these conditions, the electron concentration in the discharge plasma would reach 2 x 10^{13} cm^{-3}.

The Leningrad Polytechnic and Yefremov institutes have jointly developed the concept of using the field-emission diode of a high-current electron accelerator as a fast opening switch [141]. The switching process in the diode occurs in two stages: the first stage is represented by the microtip explosion at the cathode surface; the second stage sets in when the cathode is covered by a plasma layer. The current I_a of the first stage, due to field emission, is a function of the interelectrode gap d. The current I_n of the second stage emitted by plasma is a function of d^2. The design of the diode is based on the choice of d, such that $I_a >> I_n$. In this case, the current cut-off time t_i is determined by the thermal microtip explosion process. If the velocity of the ionized vapor of the cathode material is low enough ($v \approx 2 \times 10^6$ cm/sec) and the thickness of the cathode plasma layer $\Delta d = vt_i << d$, the contribution from I_n becomes negligible for $t > t_i$. Furthermore, at $t > t_i$ the gap resistivity is expected to exceed its initial value significantly when the high-voltage pulse appears at the cathode. This rise of resistivity follows directly from the fact that cathode surface whiskers are smoothed to a considerable extent during the explosive emission process and, in addition, become covered by the plasma layer, whose conductivity drops smoothly towards the anode.

This switching concept was tested experimentally with the REP-5 electron accelerator and theoretically by numerical simulation. The experiments involved a coaxial pulse-forming line and a tubular cathode with an outer radius $r_k = 1$ cm and an edge curvature radius $r_0 = 0.02$ cm. Two values of d, 1.3 and 2.8 cm, were used. The results show that for $d/r_k \gtrsim 2$, $I_a >> I_n$, so that the current (of about 35 kA) can be considered cut off in 5 nsec. The current drop was accompanied by a voltage jump at the gap from 1.5 MV to 6 MV. (If the switch and diode inductances are assumed to be zero, the voltage peak should be 3 MV.) At the same time, the ratio of diode-to-line impedance increases by a factor of 100.

The self-restoring mechanism of the field-emission cathode renders the proposed opening switch repetitive in principle. No changes in the volt-ampere characteristic of the system were observed in the experiments after 1000 shots. The advantage of this switch design is that it can use the available diode hardware for nanosecond high-current accelerators. It is expected that this hardware can yield switches for 50 to 500 kA and 1 to 10 MV.

A systems approach to the problem of opening switches for high-current accelerators powered by inductive energy storage was developed by a team led by Ye. G. Komar, the late director of the Yefremov Institute, and O. A. Gusev, its deputy director for research. The stated objective of this work was to exceed significantly the current operational accelerator parameters of 1 MJ per pulse at 1 to 10 MV. The obvious method of achieving higher parameters is the use of inductive storage in place of the capacitor banks.

The team proposed several designs, some of which were based on the use of an auxiliary electron beam in the operation of the switch [142]. The simplest design, connecting the inductive store directly to the accelerating diode, features an auxiliary power supply and control electrode for an electron beam shunting the switch. Gusev and Komar were awarded an author's certificate [143] for this design (Fig. 19).

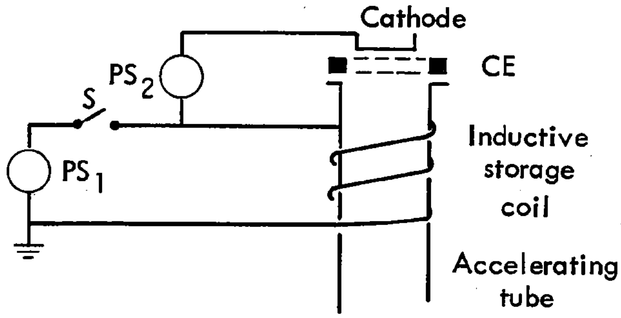

Fig. 19--Electron accelerator with a 1-MV inductive storage switch

After energy is transferred from power supply PS_1 to the inductive storage coil, switch S disconnects PS_1 from the inductor and the inductor emf appears across the diode gap. The operation of switch S is markedly improved if a charged-particle beam is allowed to pass through the accelerating tube before switch S is opened. This is accomplished by means of auxiliary power supply PS_2 and control electrode CE. Because the beam electrons fall on a grounded collector, the electron beam effectively shunts out the charging circuit of the inductive store. If the beam current is equal in magnitude to the current through the coil of the inductor, the current in switch S will be zero and the switch can be opened without arcing. After switch S is opened, the voltage across the terminals of the inductor can be varied by reducing the voltage of the control electrode. The inductor voltage is then obviously equal to the product of coil inductance and the derivative of the electron beam current. By controlling the beam current derivative, one can produce rectangular or any other pulse shape of the accelerating voltage. Furthermore, the presence of the magnetic field in the inductor can be used to focus the beam. In this design, nearly all of the energy stored in the magnetic field of the inductor (except for the coil heating loss) is expended on the acceleration of charged particles. The energy loss increases considerably if the electron-beam shunt is replaced by more conventional switching techniques, such as exploding wires and foils.

The team has also developed another variant of the inductive storage accelerator according to which the inductor is represented by a transformer. For a fixed maximum switch voltage, the beam

current and the efficiency of energy transfer in such a design become functions of the coefficient of transformation. Further increases in beam energy can be obtained by staging several inductors in series.

The Yefremov Institute has built experimental prototypes of the accelerator design shown in Fig. 19 and of the variant featuring a transformer inductor. The former design is used to test the beam-focusing properties of the magnetic field generated by the storage inductor, rectangular voltage pulse forming, and the operation of the switch at 1 MV using the controllable electron beam shunt. The latter design uses a field emission cathode and an exploding-foil opening switch. The inductor is also mounted coaxially with the accelerator tube. The resulting beam, 0.5 cm from the anode, was 1 kA, 300 kV, 7 μsec, 2 cm in diameter [142].

In the experiments with the controllable electron beam shunt (Fig. 19), nonarcing performance of the switch was obtained when the beam shunt was adjusted by the control electrode so as to produce a rectangular pulse shape, provided the beam current was equal to the current in the inductor. However, the limited value of the beam current then imposed a limit on the inductor current. The required quantity of stored energy must consequently be provided by increasing the number of turns of the winding; this increase, in turn, increases the parasitic capacitance affecting the control electrode and the inductor.

The team investigated the optimum operation of the control electrode for minimizing the parasitic capacitance losses, using an inductive storage system for a 1-MeV, 1-A proton source [144].

While this team has been concerned with the development of charged-particle accelerators, and in particular with the focusing of electron beams in the magnetic field of the inductive storage systems [145], it has also participated in switch development. Its contribution in this area was a two-stage opening switch in which the first stage is a vacuum circuit breaker with liquid-metal contactors driven by a solenoid and the second stage is a high-power cold-cathode

gas discharge tube. The vacuum switch opens in 10 μsec when shunted by the tube when the current is near zero. The switch has been designed for 500 kA, 50 kV, 0.2 sec, and a voltage rise rate of 2 kV/μsec. An experimental prototype of the switch was tested at 100 kA, 30 kV, and voltage rise rate of 1.5 kV/μsec [146].

4. Mechanical Opening Switches

The Yefremov Institute designed an opening two-stage switch actuated by compressed gas driving a contactor piston [139]. In the first stage of the operating cycle, current is allowed to flow during the charging mode and is then interrupted in the second stage under arc-less switching conditions. The maximum operating voltage of the switch is 50 kV at 40 kA. The switching time is 1 msec.

V. G. Artyukh and S. A. Smirnov (whose affiliation is not known) were awarded author's certificate No. 387451, published in 1973, for a fast-acting mechanical switch with liquid-metal contacts [147]. The switch, capable of dumping 12 kA currents into a 6×10^{-4}-ohm resistive load in tens of μsec, consists of a stack of parallel ceramic plates with holes which in the closed position form a hollow column 1 cm^2 in cross-sectional area filled with liquid metal (eutectic alloy of indium and gallium). In the closed position, the switch can conduct up to 15 kA for 50 msec. The switch is opened by sliding alternate plates out of alignment, with a velocity of 4 m/sec, breaking the conducting column into a series of isolated pieces. The stack is immersed in transformer oil to increase its electric strength and reduce friction. Measurements of the electric strength of the open switch showed an excess over 10 kV dc for two plates and a 1-mm interelectrode gap.

X. SPARK GAPS AND CLOSING SWITCHES

Spark gaps as elements of capacitive storage systems and nanosecond pulse generators have recently received considerable attention, particularly from the Leningrad group, as represented by the Leningrad Polytechnic Institute (LPI) and the Yefremov Institute. Substantial development work has also been done at the Institute of Nuclear Physics, Electronics, and Automation of the Tomsk Polytechnic Institute (TPI). The following are the principal authors affiliated with these institutes who are pursuing the work on spark gaps and closing switches:

Leningrad Polytechnic Institute: P. N. Dashuk and G. S. Kichayeva

Tomsk Polytechnic Institute: Yu. P. Usov and N. S. Rudenko

Yefremov Institute: A. M. Stolov, F. M. Spevakova, B. G. Karasev, and V. N. Skripunov

Unidentified institutes: E. A. Avilov and V. A. Alekseyev

Table 4 compares the basic operating parameters of U.S. and Soviet spark gaps and closing switches. Soviet switches are discussed in greater detail in the following subsections.

A. VACUUM GAP SWITCHES

The LPI has developed several vacuum gap switches for repetitive closing of capacitive storage lines. The new design, characterized by relatively short delay time and low jitter, is said to eliminate the high-voltage problems. One type of vacuum spark gap switch is designed for 100 kV, 1.5 MA, with a delay time of 0.2 μsec, 20-nsec jitter, and 15-nH switch inductance. The design features cylindrical chambers in series equally dividing the voltage and separating three electrode discs. Each chamber houses three starting electrodes uniformly spaced along the perimeter. The starting voltage pulse of 25 kV and 50-nsec rise time initiates a discharge on the surface of the starting electrode housing.

Table 4

SPARK GAPS AND CLOSING SWITCHES

	V,kV	I,kA	Delay Time	Jitter	Remarks	Developer	Year	Ref.
			Soviet Designs					
Vacuum spark gap	100	1500	0.2 μsec	20 nsec	4000 shots	LPI	1975	148
Vacuum spark gap	50	1000	0.2 μsec	20 nsec	5000 shots	LPI	1975	149
Laser-triggered vacuum gap	1-10	--	2.3 nsec	--	--	--	1975	150
SF_6 spark gap	700	35	--	--	T_{volt}[a] = 2%	TPI	1975	151
SF_6:N_2 spark gap	1000	--	--	2 nsec	TONUS, 2000 shots	TPI	1976	152
H_2 spark gap	250	1	1 nsec	--	T_{volt}=2%, 10^6 shots	--	1973	154
Solid dielectric spark gap	20	100	--	--	2 H_2 repetition rate, 2200 shots	--	1975	155
Sliding discharge gap	0-40	500	40 nsec	10 nsec	--	LPI	1976	156
Liquid-metal switch	50	600	--	--	0.1-sec pulse	YEF	1976	126
Pneumatic switch	--	100	--	--	Several-sec pulse	YEF	1974	136
Electrodynamic drive switch	50	75	--	--	--	YEF	1974	136
			U. S. Designs					
Thyratron	120	10	100 nsec	--	--	ECON	1976	160
Semiconductor thyristor	50	30	500 nsec	--	--	W[b]	1976	160
Gas spark gap (projected)	300	--	--	--	250 pps repetition rate, 5 MW	Maxwell	1976	160
Crossed field switch	40	10	10 μsec	--	125 pps rep rate 0.5 MW	Hughes	1976	160
Vacuum arc	5	3	1 μsec	--	--	SUNY	1976	160
Liquid-metal plasma valve	150	1.8	--	--	60 H_2 continuous	Hughes	1976	160
Laser-controlled gap								
Gas	3000	--	<1 nsec	<1 nsec	50 pps rep rate	IPC[c]	1976	161
Solid	85	--	3 nsec	3 nsec	--	AFWL	1976	161
Vacuum	7	2	1 μsec	1 μsec	--	Cornell	1976	161

[a]The parameter T_{volt} represents voltage stability from shot to shot, defined as the RMS deviation from the arithmetic mean amplitude of voltage.

[b]Westinghouse Corp.

[c]Ion Physics Corp.

The delay time τ_1, defined as the time between the starting voltage pulse and the discharge current's reaching 600 A, was measured as a function of gap electrode voltage. The delay time decreased asymptotically with increasing voltage, reaching 0.2 μsec above 80 kV, with jitter dropping to 20 nsec. The electric strength of the internal insulation of the gap switch was tested for repetitive switching of currents in the range from 100 kA to 1.5 MA. The switch itself was tested in each of two circuits with the following parameters:

1. $V_{0_{max}}$ = 100 kV, W_{max} = 10 kJ, f = 300 kHz, I_{max} = 300 kA, and oscillation decrement δ = 1.5.

2. $V_{0_{max}}$ = 50 kV, W_{max} = 60 kJ, f = 40 to 120 kHz, I_{max} = 500 to 1500 kA, and δ = 1.5.

The first circuit was subjected to 1000 shots, the second to 3000 shots. After each 100 shots, the internal insulation was examined by connecting the switch to a dc source and measuring the breakdown voltage. The latter was found to be in the range of 125 to 145 kV.

Special experiments were run to verify the capability for repetitive switching of relatively low currents (100 kA), inasmuch as self-cleaning is not as effective at lower current for organic glass insulators. After 100 shots switching 100 kA current, the electric strength of the switch decreased to 95 kV. The electric strength was restored to 120 kV after a few shots switching 400 kA. Repetitive switching (over 500 shots) of 1000- to 1500-kA currents maintained the electric strength at 120 kV. The switch continued to operate after 4000 shots, the internal surface of insulators retained its polish, and electrode erosion was confined to the center with a diameter of 80 to 100 mm [148].

Another LPI vacuum spark gap type switch has been designed for repetitive closing of megampere circuits at 50 kV in 50 kJ capacitive storage systems. Two variants of the switch have been developed, one

with plane disk electrodes and the other with coaxial electrodes to reduce erosion. In the coaxial version, the parallel disks evolved into a bell-shaped configuration to guide the plasma discharge channel, propelled by electromagnetic force, towards the bottom of the bell. In both versions, the pressure varied from 0.00133 to 0.133 Pa and a 100-liter buffer reservoir was used to lower the pressure in the chamber after the passage of the high current. The discharge was initiated by three trigger electrodes spaced around the periphery of the main electrodes to decrease the delay time and to ensure uniform current distribution. The main steel electrodes, 300 mm in diameter, were spaced 32 mm apart. The inductance of the switches with coaxial leads was 6 nH.

In the optimal case, at a pressure of 0.266 Pa, the delay time was 0.26 μsec at 5 kV and 0.19 μsec at 50 kV. The root-mean-square deviation did not exceed 10 percent. The switches sustained up to 5000 shots at 1-MA currents with high reliability and within a broad range of voltages (from 1 to 50 kV). The coaxial version of the switch is considered particularly suitable for repetitive operation (10^4 shots) in systems designed for 50 kJ at 50 kV and 1 MA. The high accuracy of these switches and short delay times ensure the possibility of synchronized operation of a large number of units in large energy storage systems [149].

Soviet scientists have also been developing laser-triggered gap switches in gaseous media and in vacuum. Although such efforts are beyond the scope of this report, the recently published experimental data on a laser-triggered vacuum switch may serve to illustrate Soviet work in this area. The developers of this switch are V. S. Bulygin, V. B. Lebedev, G. A. Pryanikova, V. V. Ryukkert, S. S. Tsitsiashvili, and V. A. Yakovlev [150]. They claimed the shortest delay time (2.3 nsec) of all the vacuum switch work reported in the literature. Their switch, inserted in a 75-ohm line, had a voltage range of 1 to 10 kV, gap width of 1.8 mm, and vacuum of 5×10^{-6} Torr. The pulse forming line provided a pulse length of 125 nsec. The gap consisted of two titanium disc electrodes 15 mm in diameter and 0.2 mm thick.

A Q-switched ruby laser with a beam pulse length of 25 to 30 nsec was used for initiation. The switch was tested for both cathode and anode initiation modes. The following are the principal test results for each mode.

	Cathode Initiation	Anode Initiation
Threshold laser energy, mJ	0.15	0.3
Average laser energy density of focal spot, J/cm^2	0.5	1
Average laser power density, mW/cm^2	10	20
Pulse rise time, nsec	Several 10s	
At threshold	--	20
Above threshold	--	3 to 5
Delay time, nsec	--	2.3

B. GAS-FILLED SPARK GAP SWITCHES

The Institute of Nuclear Physics, Electronics, and Automation of the Tomsk Polytechnic Institute (TPI), together with the Joint Institute for Nuclear Research in Dubna, has been investigating voltage stabilization problems in gas-filled spark gap switches.

The shot-to-shot variation of voltage was investigated for three types of gap switches: a three-electrode gas gap, a two-electrode gas gap with shaped cathode, and a two-electrode gap filled with liquid dielectric. The gaps were tested at 700 kV and 35 kA from a Marx generator. In the three-electrode gap filled with SF_6 at 5 atm, $T_{volt} = \pm 0.96\%$. However, the three-electrode gap can be used to stabilize pulse voltage only if the pulse has a flat section. For the two-electrode gap filled with transformer oil, $T_{volt} \leq 2\%$ [151].

Voltage stabilization was also investigated to determine the best material for gas-filled gap electrodes. Experiments were performed with 100 kV Marx generators (> 10^4A) for breakdown voltage stability in repeated shots. The gap switches contained the two electrodes in a cylindrical or barrel housing of organic glass filled with gas at 3 to 4 atm. The electrode materials tested included two tungsten alloys, TNC (95% T, 3% Ni, 2% Cu) and TNF (90% T, 7% Ni, 3% Fe), graphite, and tantalum, used as a 35-mm insert in a brass electrode. The housings were 100 mm (cylinder) and 160 mm (barrel)

in diameter, the housing wall-to-electrode distance was 25 mm (cylinder) and 55 mm (barrel), the interelectrode gap was 1 to 2 cm. The gases used were air, technical N_2 (0.5% O_2), pure N_2 (0.003% O_2, < 0.02 g/m^3 moisture), and CO_2. The tests were intended to determine the effect of two factors on the breakdown voltage: thermal wear of the electrode material and contamination of the internal switch surface with the products of chemical reactions. The results showed that tantalum and TNF electrodes with CO_2 are the most suitable for Marx switches [152].

The TPI recently reported more data on the multichannel spark-gap switches developed for its TONUS electron accelerator. According to the TPI, compressed-gas switches are preferable to vacuum spark gaps for MV pulses over 10^5 A. The pulse front length t_f for a single-channel switch, disregarding the discharge circuit inductance, is determined from the empirical formula

$$t_f = I \cdot 10^{-13} \text{ sec} \qquad ,$$

where I is the switched current in amperes. It follows that for 10^5 A currents and t_f < 15 to 20 nsec, multiple switches operating in parallel are needed. Parallel operation in this case, however, requires a jitter value of 1 nsec or less.

The TPI tested the spark gap switching system used for the past three years in the 1-MV TONUS accelerator. In the test, two three-electrode switches were triggered by one two-electrode switch. The purpose of the test was to determine the value of jitter τ, as affected by spark UV and overvoltage and by field distortion at the gaps. The spark UV illumination was obtained from the two-electrode starting switch; the overvoltage was set up in the gaps of the three-electrode switches after the breakdown of the starting switch. The switches were supplied with a 200-kV, 250-nsec pulse from a Marx generator. The lowest value of jitter (0.5 nsec) was observed when the spark UV and overvoltage occurred simultaneously. The 0.5-nsec jitter is the RMS value obtained in 100 events. Spark

UV or overvoltage alone yielded τ of 6 and 10 nsec, respectively. In the distorted-field tests, the lowest value of τ was 1.4 nsec.

The switch system used in the TONUS accelerator operates as follows: The switches are arranged to ensure the simultaneous UV spark and overvoltage action yielding the lowest jitter. The system consists of four three-electrode gap switches set in a square pattern, with the fifth two-electrode starting switch in the center of the square. All the gap switches were filled with a mixture of 30 percent SF_6 and 70 percent N_2. A Marx generator charges a Blumlein line so that one-half of the charging voltage appears in 1 μsec at the center electrode of each three-electrode gap switch. The two-electrode starting switch operates when full voltage is reached at the Blumlein. Suitable adjustment of gas pressure and gap width in all switches ensures that only the starting switch breaks down at the peak of the charging pulse. An inductance built into the central electrode of the three-electrode gap switch generates the required overvoltage which together with the intense UV illumination from the starting switch spark keeps the jitter low. The switch system has proved reliable and simple to maintain in three years of operation. The RMS value of the jitter for two three-electrode gap switches was 2.26 nsec after 5000 shots without gas replacement or overhaul [153].

A miniaturized high-pressure hydrogen-filled 250-kV spark gap reported in 1973 has a 1-nsec switching time, T_{volt} of 1.5 percent, and a service life of 10^6 shots at 50 Hz pulse repetition rate. The electrodes are made of flat tungsten alloy plates with rounded edges. The 1-nsec switching time (length of the voltage pulse front) was obtained when a 25-pF coaxial capacitor was discharged across the switch filled with H_2 at 40 atm into a 3-kohm resistor. The switched energy was 0.5 J and peak current was 1 kA. A series of gap switches of this type, 30, 40, and 50 mm in diameter, has been developed for production for 100, 150, and 250 kV, respectively. After 10^6 shots at 0.5 J of switched energy and 50 Hz, no changes were observed in their operating characteristics [154].

C. SOLID-DIELECTRIC GAP SWITCHES

An interesting design for high currents features a solid dielectric in the form of a moving tape. The switch handles 100-kA, 20-kV, 200-nsec pulses with a repetition frequency of 2 Hz. The electrode inductance of the switch is 5 nH. The dielectric between the two flat brass electrodes, separated by a 0.5 mm gap, is fluoroplastic tape, 100 to 200 μm thick and 90 mm wide, moved by a transport mechanism. The discharge current is initiated by a 4-mm needle puncturing the tape. The distance between successive punctures is 45 mm. In operation, a 100 m tape yields 2200 shots. The switch is intended for low-inductance circuits generating short current pulses at high voltages, such as pump lamps for organic dye lasers. An advantage of this type of switch is the absence of starting systems normally required by triggered switches of other types [155].

The LPI developed a different switch principle for high currents involving solid dielectrics. This is a multichannel air-discharge switch in which the discharge is developed on the surface of a solid dielectric sheet. LPI scientists believe that this switch design has successfully met all the basic requirements--minimal inductance and internal impedance of the gap, wide range of operating voltages, short switching time, and low jitter--for spark gaps used for current switching in capacitive storage systems. The switch operated reliably within the voltage range of 0 to 40 kV handling currents up to 500 kA. The maximum capacitor bank energy was 11.5 kJ, and the total inductance of the switch circuit was 66 nH. The operating time of the switch was 40 nsec with a 10 nsec jitter. The sliding-discharge switches, expected to operate reliably with 2-MA currents, are suitable for parallel and crowbar operation [156].

D. MECHANICAL CLOSING SWITCHES

The Yefremov Institute of Electrophysical Equipment has developed a series of high-current mechanical closing switches. An interesting design employs exploding wires submerged in liquid metal. In an experimental prototype, one of the two power circuit electrodes was

a box filled with Na-K eutectic; the other electrode was suspended above the surface of the liquid metal. The switch housing had an airtight seal. An exploding wire was submerged in the eutectic, which was electrically connected to the end of the wire. The wire explosion ejected the liquid metal upward, closing the switch. The liquid metal then returned to the initial state by gravity, breaking the circuit. The distance between the liquid surface and the upper electrode was 10 mm; the operating time was about 0.2 msec for 3 to 4 kJ delivered to the exploding wire from an external capacitor.

The switch was tested in the circuit of a homopolar generator delivering 4 MJ, 600 kA to the load, with a 0.1- to 0.5-sec pulse length and 0.1- to 0.5-msec pulse front. The generator voltage reached 50 V during the tests. The current density at the contact point reached 40 A/mm^2. The oscilloscope current traces showed that the duration of the closed state of the contact elements and the velocity of the liquid metal were sufficient to eliminate arcing. The internal surfaces of the switch had no traces of erosion after repeated operation. The exploding wire could be rapidly replaced without contaminating the liquid metal [126].

Electrodynamic and pneumatic devices developed by the Yefremov Institute have been applied to closing switches. These high-current switches feature film insulation and moving contactor elements with a sawtooth shape. When the switch is actuated, the point of the sawtooth cuts through the film insulation into the surface of the moving element. The electrodynamic variant of the switch is designed for 75 kA, 50 kV, and a pulse length of 1 sec. The pneumatic variant can handle several hundred kA for several seconds [138].

XI. CONCLUSIONS

The development of pulsed power in the Soviet Union is directed toward a broad range of technological applications, some explicitly stated, others implicit in the performance data of the various systems. Of the officially designated applications of pulsed power, controlled fusion energy has been receiving the greatest attention. High-current electron accelerators represent an equally important application of pulsed power. Another area of Soviet technology that may utilize the results of pulsed-power R&D to a significant extent is the long-distance transmission of electric power. There are indications that the Soviet Union may experience greater difficulty keeping up with future requirements for transmission capacity than for generating capacity.* Advanced electric-power transmission technology depends on many aspects of pulsed-power R&D, particularly, high-voltage insulation and switching systems.

What Soviet officials and scientists are saying about the intended application of pulsed-power R&D, however, is unusually vague even by Soviet standards. The Soviet press frequently observe that modern experimental physics is finding rapidly expanding uses for megajoule millisecond pulsed magnetic fields. In addition to controlled thermonuclear reactions, plasma physics and large bubble chambers are mentioned specifically as areas of application of advanced pulsed-power systems. In the context of these applications, such systems are considered to be alternatives to large capacitor banks, promising lighter and smaller structures, greater economy, higher efficiency, and above all, higher density of the stored energy.

The paucity of official comments notwithstanding, the evidence gathered in this report reveals the importance of pulsed-power R&D to the Soviet Union. Foremost among this evidence is the status accorded pulsed power in the planning of electric-power development

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*Ye. A. Abramyan, private communication.

by the Academy of Sciences, USSR.* In this respect, Soviet pulsed-power R&D is unique: In no other country is it included in the overall electric energy development program, let alone accorded so prominent a place.

The stress on pulsed power is first of all evident in the structure and plans of the Scientific Council on Theoretical and Electrophysical Problems of Electric Power. One section of the council appears at

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*The widespread, but erroneous, impression in the West that the Soviet Academy of Sciences is devoted largely, if not exclusively, to basic research may be due to the frequent Soviet references to the academy's mission as planning, coordination, and the performance of theoretical research. But *theoretical* is not synonymous with *basic* or *fundamental*. Similarly, the *theoretical* in the name of the Scientific Council for Theoretical and Electrophysical Problems of Electrical Energy does not preclude the experimental work explicitly mandated by the academy for each of the council's key areas of interest. For example, the mandate covers "theoretical, electrophysical, and experimental problems associated with the creation of extreme-parameter power plants," and "engineering problems of energy conversion in thermonuclear reactors." These programs, covering the range of research from applied science to development, must obviously include the construction and operation of advanced prototypes. In pursuing these programs, the council coordinates the work of the research institutes of the Academy of Sciences, USSR, and of the republic academies, the R&D institutes of the industrial ministries, and production plants (such as the Elektrosila Plant and the Leningrad Metal Plant).

Some of the basic institutes of the academy are also involved in the advanced stages of the research-production cycle. The Kurchatov Institute of Atomic Energy, for example, performs basic research in nuclear, solid-state, and molecular physics, various branches of chemistry, and molecular biology. It also pursues applied research and development in conjunction with design organizations. Over 90 percent of the Soviet atomic power plants installed or projected have been based on the Kurchatov design and put into operation under its guidance [157].

In view of these functions, the Academy of Sciences emerges as a planner, performer, and coordinator of advanced technology development. There are, of necessity, limits to the academy's technological involvement; in applied research and development, the academy appears to be confined to selected areas of science and technology, one of which is electric-power development. In this area, the academy is clearly expected by its leadership to advance the state of the art substantially beyond the currently achievable world levels, particularly in the size and type of the generating equipment, in the efficiency of the transmission systems, and in pulsed power.

this time to be devoted exclusively to pulsed-power R&D; a number of the remaining sections deal with various aspects of pulsed-power development as part of their programs. The background of the council's chairman, M. P. Kostenko, is of interest in this respect. Together with Petr Kapitsa, Kostenko designed the first practical pulsed-power generator in the Soviet Union. The generator produced a pulse shape necessary for the induction of high-power constant magnetic fields. The appointment of M. P. Kostenko to head the council in 1968 may well have reflected the intention of the academy's leaders to emphasize pulsed power from the council's inception. Such a conjecture is supported by the finding of this report that a comprehensive R&D effort in pulsed power began in the Soviet Union in the mid-1960s. One of the reasons for the establishment of the council a few years later could thus have been the need to coordinate the various phases of the new research, which was deemed important enough to be brought within the framework of national energy R&D.

Various events, in addition to the activities of various core research institutes, indicates the significance of the period 1965-1970 to the Soviet pulsed-power effort. A. D. Sakharov's basic paper [158] on the first significant experiments with and the possibilities for the use of explosive magnetic generators was published in 1965. Several review papers on the potentials of high-density energy storage as applied to physical research [95,107,159] appeared during succeeding years. The number of active authors publishing on the subject of pulsed power in core institutes alone more than doubled during this period, which also marked the appearance of research papers on all the major components of pulsed power within the scope of this report, including (in 1970) sophisticated advanced switching systems. Since 1970, the development of switching has progressed in proportion to that of the rest of the pulsed-power activities.

The scale of high-performance switching R&D was revealed in the massive volume of documentation on that subject published by the Yefremov Institute in 1974, on the occasion of the U.S.-Soviet seminar on the construction of thermonuclear electric-power plants. The

documentation revealed the names of 40 new authors at the Yefremov Institute alone. Although the Scientific Council on Theoretical and Electrophysical Problems of Electric Power was not mentioned in connection with the 1974 seminar, the council's sponsorship of the seminar was implied by its mandate and by the subject of the seminar, thermonuclear energy conversion, which was also the council's principal focus of attention in 1974. Although fusion energy was the context of the Yefremov Institute's publications on switching R&D, the extent of the work reflected in these publications appeared to exceed considerably the present needs of fusion research. The Yefremov's switching research, in going beyond fusion requirements, parallels the work of Section 4 of the council, which also appears to have technological applications other than fusion R&D.

Soviet work on advanced types of opening and closing switches, at the Yefremov Institute and elsewhere, shows considerable ingenuity and originality of technical solutions and methods of approach. Many of the Soviet switching designs appear particularly suitable for work with inductive storage systems, exhibiting the use of a broad range of principles, including high-explosive breakers, mechanical actuation, and controlled gas discharge. Soviet switch design practice differs from that in the United States, which tends to favor fewer, relatively proven switch types. The Soviet philosophy of switch design also seems to contradict the U.S. perception of Soviet design practice in general, that is, that Soviet designers prefer the incremental development of proven designs.

The Soviet literature on switches also reveals some interesting omissions. First, semiconductor switches for highly precise timing are not listed among advanced Soviet switches, an omission that may be due to the difficulties that the Soviets have experienced with solid-state electronics in general. Second, although many of the switches are repetitive (see tables 3 and 4), their repetition rates are seldom given in the Soviet technical literature. This is true of switches used in most Soviet pulsed-power systems, particularly of those in Soviet electron accelerators. The most plausible conclusion to be drawn from the relative absence of pulsed repetition

rates is that such data are sensitive in the military context of pulsed-power applications. As noted above, the scope of Soviet pulsed-power R&D appears to be much larger than that required for the explicitly stated purposes of Soviet activity in this area, namely, the conversion of energy from controlled thermonuclear reactions. But, because prototype design and testing of MHD generators for fusion energy would be premature at this time, it seems reasonable to infer the existence of other objectives of the ongoing pulsed-power R&D, including such military objectives as directed-energy weapons.

The possibility of military objectives of pulsed-power research is further reinforced by the Soviet preference for inductive storage as the solution to power supply, mainly because of size and weight considerations. Inductive storage, in turn, demands the intensive development of advanced switching, the abundant evidence of which in Soviet R&D may thus be interpreted as willingness on the part of the Soviets to pay the price of minimizing the size and weight of their systems.

Controlled fusion reaction calls for energy levels of the order of 10^9 J at most. The fact that the specified target levels of pulsed-power development are aimed far above this level can be interpreted as another indication of weapons application. The excess over and above the needs of CTR research extends also to the number of workers and the number and variety of R&D projects. This abundance creates an impressively broad research base, permitting the Soviet Union to seize upon more new scientific opportunities promising significant payoff than are available to the United States.

It is not possible from the foregoing discussion alone to conclude that the list of actually pursued applications of Soviet pulsed-power R&D includes directed-energy weapons. It is highly probable that it does. The basic conclusions that can be drawn about Soviet pulsed-power R&D are:

1. It is a major component of the national energy R&D.
2. It is being performed at a high level of coordinated effort.
3. Although CTR power conversion is its officially designated principal target, its scope appears excessive for the possibilities of near-term CTR application.

Appendix A

PULSED-POWER FACILITIES AND STAFF AUTHORS

The four pulsed-power research groups discussed in the text are listed below to show the institutes comprising each of the groups, the research areas in which each institute is engaged, the personnel involved, and the years during which each researcher worked in the subject area.

THE LENINGRAD GROUP

YEFREMOV INSTITUTE OF ELECTROPHYSICAL EQUIPMENT

Electromagnetic Flux Compression

Andreyev, V. R.	1973-75	Komin, A. V.	1973-75
Churayev, V. A.	1974-75	Lobanov, K. M.	1974-75
Chvartatskiy, R. V.	1973-75	Malyshev, I. F.	1973-75
Dyatlov, V. D.	1974-75	Medvedev, E. D.	1973-75
Fedyakov, V. p.	1974-75	Morozov, Yu. A.	1973-75
Frolov, A. D.	1973-75	Spevakova, F. M.	1973-75
Glukhikh, V. A.	1973-75	Spirchenko. Yu. V.	1973-75
Ivlev, A. V.	1973-75	Timonin, A. M.	1971-73
Kibardin, A. S.	1973-75	Zheltov, V. A.	1973-75

Switching

Andreyev, V. R.	1974-75	Markov, V. B.	1973-75
Atalikov, M. M.	1974-75	Mellekh, Ye. M.	1974-75
Bystrov, M. N.	1974-75	Monoszon, N. A.	1974-75
Dubovoy, L. V.	1974-75	Morozov, Yu. A.	1974-75
Fidel'skaya, R. P.	1973-75	Nechayev, A. G.	1974-75
Frolov, A. D.	1974-75	Pauchenko, N. N.	1974-75
Galkina, T. G.	1974-75	Pavlov, Ye. P.	1974-75
Glukhikh, V. A.	1973-75	Potekhin, S. P.	1974-75
Gusev, O. A.	1971-75	Royfe, I. M.	1974-75
Ivlev, A. V.	1974-75	Rudenko, A. A.	1974-75
Kalmykov, Yu. K.	1974-75	Seredenko, Ye. V.	1974-75
Karasev, B. G.	1974-75	Shirochin, L. A.	1974-75
Kibardin, A. S.	1974-75	Silin, V. P.	1974-75
Komar, Ye. G.	1971-75	Skripunov, V. N.	1974-75
Komarov, P. V.	1974-75	Spevakova, F. M.	1974-75
Komin, A. V.	1974-75	Stekol'nikov, B. A.	1974-75
Krylov, V. A.	1974-75	Stolov, A. M.	1974-75
Kuchinskiy, V. G.	1970-75	Svin'in, M. P.	1973-75
Kuznetsov, V. S.	1973-75	Uralov, S. N.	1974-75
Larinov, B. A.	1974-75	Zablotskaya, G. R.	1975-76
Lavrov, I. V.	1974-75		

Homopolar Machines

Glukhikh, V. A.	1974-75	Karasev, B. G.	1974-75

Superconductive Energy Storage

Churakov, G. F.	1973-75	Rozhdestvenskiy, B. V.	1973-75
Dinaburg, L. B.	1973-75	Sabanskiy, I. I.	1973-75
Frolov, A. D.	1973-75	Spevakova, F. M.	1973-75
Gurin, S. P.	1973-75	Trokhachev, G. V.	1973-75
Kostenko, A. I.	1973-75	Yegorov, S. A.	1973-75
Monoszon, N. A.	1973-75	Yudakov, Yu. V.	1973-75

LENINGRAD POLYTECHNIC INSTITUTE

Department of High-Voltage Engineering

Electromagnetic Flux Compression

Gordiyenko, V. P.	1963-65	Novgorodtsev, A. B.	1964-72
Knyazev, V. P.	1970-72	Shcherbakov, A. P.	1970-75
Kuchinskiy, V. G.	1973-75	Shneyerson, G. A.	1961-75
Mikhkel'soo, V. T.	1969-75		

Switching

Dashuk, P. N.	1974-76	Markov, S. N.	1975-76
Drozdov, A. A.	1975-76	Shkuropat, P. I.	1974-76
Grigor'yev, A. V.	1975-76	Shutov, V. L.	1975-76
Ikonnikov, V. B.	1974-76	Yarysheva, M. D.	1975-76
Kichayeva, G. S.	1974-75	Yefimov, B. V.	1975-76
Kubar'kov, Yu. P.	1975-76		

Unspecified Department

Homopolar Machines

Agaronyan, G. N.	1965-67	Yurinov, V. M.	1965-75
Kharitonov, V. V.	1970-75	Zlobina, O. A.	1974-75

THE MOSCOW GROUP

KURCHATOV INSTITUTE OF ATOMIC ENERGY

MHD Converters

Belykh, A. D.	1972-75	Panchenko, V. P.	1974-75
Breyev, V. V.	1974-75	Velikhov, Ye. P.	1973-75
Chernukha, V. V.	1973-75	VItshas, A. F.	1966-68
Dmitriyevskiy, V. A.	1970-72	Volkov, Yu. M.	1974-75
Golubev, V. S.	1966-75	Yakushev, A. A.	1974-75
Gurashvili, V. A.	1972-75		

EMG Flux Compression

Azizov, Ye. A.	1973-75	Semenov, V. N.	1974-75
Breyev, V. V.	1973-75	Shipuk, I. Ya.	1974-75
Ivanov, I. A.	1973-75	Utyugov, Ye. G.	1974-75
Kurtmullayev, R. Kh.	1974-75	Zotova, Ye. A.	1973-75
Pichugin, V. V.	1974-75		

Switching

Akhmerov, N. A.	1974-76	Pichugin, V. V.	1974-75
Azizov, Ye. A.	1974-76	Shipuk, I. Ya.	1974-75
Fin'ko, S. V.	1974-75	Ulnich, F. R.	1974-75
Kochurov, I. V.	1974-75	Utyugov, Ye. G.	1974-75
Korop, Ye. D.	1974-75	Yagnov, V. A.	1974-76
Nikolayevskiy, V. G.	1974-75		

INSTITUTE OF HIGH TEMPERATURES

MHD Converters

Al'tov, V. A.	1966-70	Pishchikov, S. I.	1973-75
Asinovskiy, E. I.	1966-70	Savrov, S. D.	1968-70
Dremin, A. N.	1968-70	Shelkov, Ye. M.	1973-75
Dubovitskiy, F. I.	1968-70	Sheyndlin, A. Ye.	1966-70
Kirillin, V. A.	1966-70	Sychev, V. V.	1964-75
Kuznetsov, Yu. A.	1968-70	Zaklyazminskiy, L. A.	1970-72
Lebedev, Ye. F.	1968-70	Zenkevich, V. B.	1964-75
Maksimov, A. M.	1966-68		

Superconductive Energy Storage

Al'tov, V. A.	1968-70	Shelkov, Ye. M.	1973-75
Andrianov, V. V.	1964-73	Sheynkman, V. S.	1970-72
Kremlev, M. G.	1968-75	Sukhorukov, A. G.	1970-72
Kulysov, N. A.	1971-74	Sychev, V. V.	1964-75
Kurguzov, V. V.	1971-73	Ternovskiy, F. F.	1965-73
Pishchikov, S. I.	1973-75	Tovma, V. A.	1970-72
Popkov, O. V.	1970-72	Zenkevich, V. B.	1964-75
Sergeyenkov, B. N.	1970-72		

INSTITUTE OF MECHANICS, MOSCOW STATE UNIVERSITY

Switching

Kozorezov, K. I.	1974-75	Semchenko, V. V.	1974-75

INSTITUTE OF APPLIED MATHEMATICS

HE Flux Compression

Kalitkin, N. N.	1968-70	Tsareva, L. S.	1968-70

THE NOVOSIBIRSK GROUP

NUCLEAR PHYSICS INSTITUTE

HE Flux Compression

Deribas, A. A.	1967-69	Sobolev, O. P.	1967-69
Fedulov, A. F.	1969-71	Voytenko, A. Ye.	1967-74
Matochkin, Ye. P.	1969-74	Yablochnikov, B. A.	1972-74
Nesterikhin, Yu. Ye.	1967-69		

Electromagnetic Flux Compression

Alikhanov, S. G.	1965-69	Karasyuk, V. N.	1967-69
Belan, V. G.	1966-69	Kichigin, G. N.	1965-69
Budker, G. I.	1965-68	Komin, A. V.	1964-67
Ivanchenko, A. I.	1966-69	Yurchenko, V. I.	1972-75

Switching

Faleyev, V. A.	1973-75	Voytenko, A. Ye.	1967-75
Isakov, V. P.	1973-75	Zherebnenko, V. I.	1973-75
Luk'yanchikov, L. A.	1969-74	Zubkov, P. I.	1969-74
Novoselov, B. S.	1970-72		

INSTITUTE OF HYDRODYNAMICS

HE Flux Compression

Bichenkov, Ye. I.	1963-75	Kulikov, B. I.	1967-71
Demchuk, A. F.	1967-71	Lobanov, V. A.	1972-75

Switching

Bichenkov, Ye. I.	1974-75	Lobanov, V. A.	1974-75

INSTITUTE OF AUTOMATION AND ELECTROMETRY

Switching

Gerasimov, L. S.	1973-75	Nesterikhin, Yu. Ye.	1974-75
Ikryannikov, V. I.	1973-75	Pinchuk, A. I.	1973-75
Iskol'dskiy, A. M.	1974-75	Pinus, V. K.	1974-75

THE INDEPENDENT GROUP

TOMSK POLYTECHNIC INSTITUTE

Institute of Automation and Electromechanics

Multipolar Pulse Generators

Ivashin, V. V.	1960-68	Romanov, Yu. A.	1970-73
Khor'kov, K. A.	1964-67	Sergeyev, V. F.	1970-73

Multipolar Pulse Generators (cont'd)

Loos, A. V.	1965-75	Sipaylov, G. A.	1964-75
Perezhirov, Yu. I.	1971-73	Sobko, E. I.	1972-74

Institute of Nuclear Physics, Electronics, and Automation

Switching

Pak, V. S.	1974-76	Smetanin, V. I.	1974-76
Remnev, G. Ye.	1975-76	Tsvetkov, V. I.	1974-76
Rudenko, N. S.	1974-76	Usov, Yu. P.	1975-76
Shatanov, A. A.	1975-76		

INSTITUTE OF ATMOSPHERIC OPTICS

Switching

Koval'chuk, B. M.	1975-76	Mesyats, G. A.	1975-76

MOSCOW AVIATION INSTITUTE

Homopolar Machines

Alabin, G. P.	1973-75	Krynitskaya, I. A.	1970-72
Aliyevskiy, B. L.	1965-75	Orlov, V. L.	1971-75
Barykin, K. K.	1974-75	Sherstyuk, A. G.	1966-75
Bertinov, A. I.	1965-75	Triotskiy, S. R.	1965-67
Isayev, V. K.	1974-75		

Superconductive Energy Storage

Bertinov, A. I.	1965-75	Mironov, O. M.	1968-75
But, D. A.	1970-72	Mokin, V. S.	1971-73
Golovkin, A. V.	1968-73	Yegoshkina, L. A.	1969-75
Ionova, A. S.	1973-75	Zhemchugov, G. A.	1968-70
Manuylov, V. G.	1973-75		

JOINT INSTITUTE OF NUCLEAR RESEARCH, DUBNA

Switching

Matyushin, A. T.	1974-76	Matyushin, V. T.	1974-76

UNIDENTIFIED FACILITIES

Homopolar Machines

Andreyev, V. I.	1973-75	Kuznetsov, S. Ye.	1973-75
Khozhainov, A. I.	1969-75		

MHD Converters

Burenin, Yu. A.	1974-75	Shvetsov, G. A.	1972-75
Polyudov, V. V.	1972-74	Titov, V. P.	1972-74

HE Flux Compression

Pavlovskiy, I. A.	1974-76	Smirnov, Ye. N.	1974-76
Rutkevich, I. M.	1966-68	Suvorov, V. N.	1974-76

Multipolar Pulse Generators

Kaplan, V. V.	1965-67	Nashatyr', V. M.	1965-67

Switching

Alekseyev, V. A.	1974-76	Polyanskiy, L. Ye.	1975-76
Artyukh, V. G.	1974-76	Pryanikova, G. A.	1974-76
Avilov, E. A.	1972-74	Razin, A. A.	1972-74
Belkin, N. V.	1972-74	Ryukkert, V. V.	1974-76
Bulygin, V. S.	1974-76	Smirnov, I. V.	1974-76
Dudin, A. V.	1972-74	Smirnov, S. A.	1974-76
Kalachev, B. V.	1974-76	Trapeznikov, V. N.	1975-76
Kaminov, M. A.	1972-74	Tsitsiashvili, S. S.	1974-76
Kromskiy, G. I.	1974-76	Yakovlev, V. A.	1974-76
Lebedev, V. B.	1974-76	Zolotarev, E. I.	1975-76
Mukhin, V. D.	1975-76	Sykov, A. P.	1972-74

Appendix B

ALPHABETICAL LIST OF AUTHORS

Authors of the research described in this report are listed below in alphabetical order, along with the abbreviated name of the institute with which each is affiliated, the subject area of his research, and the years during which he was assumed to be engaged in that research. The following abbreviations are used to represent the institutes:

AEM - Institute of Automation and Electrometry (Novosibirsk)
HYD - Institute of Hydrodynamics (Novosibirsk)
IAE - Kurchatov Institute of Atomic Energy (Moscow)
IAM - Institute of Applied Mathematics (Moscow)
IAO - Institute of Atmospheric Optics (Tomsk)
IHT - Institute of High Temperatures (Moscow)
IME - Institute of Mechanics (Moscow State University)
JIN - Joint Institute of Nuclear Research (Dubna)
LPI - Leningrad Polytechnic Institute
MAI - Moscow Aviation Institute
NPI - Nuclear Physics Institute (Novosibirsk)
TPI - Tomsk Polytechnic Institute
YEF - Yefremov Institute of Electrophysical Equipment (Leningrad)
--- - Unidentified Facility

Areas of research are coded as follows:

EMG - Electromagnetic Flux Compression
HEF - HE Flux Compression
HOM - Homopolar Machines
MHD - MHD Converters
MUL - Multipolar Pulse Generators
SES - Superconductive Energy Storage
SWI - Switching

Name	Institute	Research Area	Years
Agaronyan, G. N.	LPI	HOM	1965-67
Akhmerov, N. A.	IAE	SWI	1974-76
Alabin, G. P.	MAI	HOM	1973-75
Alekseyev, V. A.	---	SWI	1974-76
Alikhanov, S. G.	NPI	EMG	1965-69
Aliyevskiy, B. L.	MAI	HOM	1965-75

Name	Institute	Research Area	Years
Al'tov, V. A.	IHT	MHD	1966-70
		SES	1968-70
Andreyev, V. I.	---	HOM	1973-75
Andreyev, V. R.	YEF	EMG	1973-75
		SWI	1974-75
Andrianov, V. V.	IHT	SES	1964-73
Artyukh, V. G.	---	SWI	1974-76
Asinovskiy, E. I.	IHT	MHD	1966-70
Atalikov, M. M.	YEF	SWI	1974-75
Avilov, E. A.	---	SWI	1972-74
Azizov, Ye. A.	IAE	EMG	1973-75
		SWI	1974-76
Barykin, K. K.	MAI	HOM	1974-75
Belan, V. G.	NPI	EMG	1966-69
Belkin, N. V.	---	SWI	1972-74
Belykh, A. D.	IAE	MHD	1972-75
Bertinov, A. I.	MAI	HOM, SES	1965-75
Bichenkov, Ye. I.	HYD	HEF	1963-75
		SWI	1974-75
Breyev, V. V.	IAE	MHD	1974-75
		EMG	1973-75
Budker, G. I.	NPI	EMG	1965-68
Bulygin, V. S.	---	SWI	1974-76
Burenin, Yu. A.	---	MHD	1974-75
But, D. A.	MAI	SES	1970-72
Bystrov, M. N.	YEF	SWI	1974-75
Chernukha, V. V.	IAE	MHD	1973-75
Churakov, G. F.	YEF	SES	1973-75
Churayev, V. A.	YEF	EMG	1974-75
Chvartatskiy, R. V.	YEF	EMG	1973-75
Dashuk, P. N.	LPI	SWI	1974-76
Demchuk, A. F.	HYD	HEF	1967-71

Name	Institute	Research Area	Years
Deribas, A. A.	NPI	HEF	1967-69
Dinaburg, L. B.	YEF	SES	1973-75
Dmitriyevskiy, V. A.	IAE	MHD	1970-72
Dremin, A. N.	IHT	MHD	1968-70
Drozdov, A. A.	LPI	SWI	1975-76
Dubovitskiy, F. I.	IHT	MHD	1968-70
Dubovoy, L. V.	YEF	SWI	1974-75
Dudin, A. V.	---	SWI	1972-74
Dyatlov, V. D.	YEF	EMG	1974-75
Faleyev, V. A.	NPI	SWI	1973-75
Fedulov, A. F.	NPI	HEF	1969-71
Fedyakov, V. P.	YEF	EMG	1974-75
Fidel'skaya, R. P.	YEF	SWI	1973-75
Fin'ko, S. V.	IAE	SWI	1974-75
Frolov, A. D.	YEF	EMG, SES	1973-75
		SWI	1974-75
Galkina, T. G.	YEF	SWI	1974-75
Gerasimov, L. S.	AEM	SWI	1973-75
Glukhikh, V. A.	YEF	EMG, SWI	1973-75
		HOM	1974-75
Golovkin, A. V.	MAI	SES	1968-73
Golubev, V. S.	IAE	MHD	1966-75
Gordiyenko, V. P.	LPI	EMG	1963-65
Grigor'yev, A. V.	LPI	SWI	1975-76
Gurashvili, V. A.	IAE	MHD	1972-75
Gurin, S. P.	YEF	SES	1973-75
Gusev, O. A.	YEF	SWI	1971-75
Ikonnikov, V. B.	YEF	EMG	1973-75
		SWI	1974-75
Ikryannikov, V. I.	AEM	SWI	1973-75
Ionova, A. S.	MAI	SES	1973-75

Name	Institute	Research Area	Years
Isakov, V. P.	NPI	SWI	1973-75
Isayev, V. K.	MAI	HOM	1974-75
Iskol'dskiy, A. M.	AEM	SWI	1974-75
Ivanchenko, A. I.	NPI	EMG	1966-69
Ivanov, I. A.	IAE	EMG	1973-75
Ivashin, V. V.	TPI	MUL	1960-68
Ivlev, A. V.	YEF	EMG	1973-75
		SWI	1974-75
Kalachev, B. V.	---	SWI	1974-76
Kalitkin, N. N.	IAM	HEF	1968-70
Kalmykov, Yu. K.	YEF	SWI	1974-76
Kaminov, M. A.	---	SWI	1972-74
Kaplan, V. V.	---	MUL	1965-67
Karasev, B. G.	YEF	SWI, HOM	1974-75
Karasyuk, V. N.	NPI	EMG	1967-69
Kharitonov, V. V.	LPI	HOM	1970-75
Khor'kov, K. A.	TPI	MUL	1964-67
Khozhainov, A. I.	---	HOM	1969-75
Kibardin, A. S.	YEF	EMG	1973-75
		SWI	1974-75
Kichayeva, G. S.	LPI	SWI	1974-75
Kichigin, G. N.	NPI	EMG	1965-69
Kirillin, V. A.	IHT	MHD	1966-70
Knyazev, V. P.	LPI	EMG	1970-72
Kochurov, I. V.	IAE	SWI	1974-75
Komar, Ye. G.	YEF	SWI	1971-75
Komarov, P. V.	YEF	SWI	1974-75
Komin, A. V.	YEF	EMG	1973-75
		SWI	1974-75
Korop, Ye. D.	IAE	SWI	1974-75
Kostenko, A. I.	YEF	SES	1973-75
Koval'chuk, B. M.	IAO	SWI	1975-76
Kozorezov, K. I.	IME	SWI	1974-75

Name	Institute	Research Area	Years
Kremlev, M. G.	IHT	SES	1968–75
Kromskiy, G. I.	---	SWI	1974–76
Krylov, V. A.	YEF	SWI	1974–75
Krynitskaya, I. A.	MAI	HOM	1970–72
Kubar'kov, Yu. P.	LPI	SWI	1975–76
Kuchinskiy, V. G.	YEF LPI	SWI EMG	1970–75 1973–75
Kulikov, B. I.	HYD	HEF	1967–71
Kulysov, N. A.	IHT	SES	1971–74
Kurguzov, V. V.	IHT	SES	1971–73
Kurtmullayev, R. Kh.	IAE	EMG	1974–75
Kuznetsov, S. Ye.	---	HOM	1973–75
Kuznetsov, V. S.	YEF	SWI	1973–75
Kuznetsov, Yu. A.	IHT	MHD	1968–70
Larionov, B. A.	YEF	SWI	1974–75
Lavrov, I. V.	YEF	SWI	1974–75
Lebedev, V. B.	---	SWI	1974–76
Lebedev, Ye. F.	IHT	MHD	1968–70
Lobankov, V. A.	HYD	HEF SWI	1972–75 1974–75
Lobanov, K. M.	YEF	EMG	1974–75
Loos, A. V.	TPI	MUL	1965–75
Luk'yanchikov, L. A.	NPI	SWI	1969–74
Maksimov, A. M.	IHT	MHD	1966–68
Malyshev, I. F.	YEF	EMG	1973–75
Manuylov, V. G.	MAI	SES	1973–75
Markov, S. N.	LPI	SWI	1975–76
Markov, V. B.	YEF	SWI	1973–75
Matochkin, Ye. P.	NPI	HEF	1969–74

Name	Institute	Research Area	Years
Matyushin, A. T.	JIN	SWI	1974-76
Matyushin, V. T.	JIN	SWI	1974-76
Medvedev, E. D.	YEF	EMG	1973-75
Mellekh, Ye. M.	YEF	SWI	1974-75
Mesyats, G. A.	IAO	SWI	1975-76
Mikhkel'soo, V. T.	LPI	EMG	1969-75
Mironov, O. M.	MAI	SES	1968-75
Mokin, V. S.	MAI	SES	1971-73
Monoszon, N. A.	YEF	SWI SES	1974-75 1973-75
Morozov, Yu. A.	YEF	EMG SWI	1973-75 1974-75
Mukhin, V. D.	---	SWI	1975-76
Nashatyr', V. M.	---	MUL	1965-67
Nechayev, A. G.	YEF	SWI	1974-75
Nesterikhin, Yu. Ye.	NPI AEM	HEF SWI	1967-69 1974-75
Nikolayevskiy, V. G.	IAE	SWI	1974-75
Novgorodtsev, A. B.	YEF	EMG	1964-72
Novoselov, B. S.	NPI	SWI	1970-72
Orlov, V. L.	MAI	HOM	1971-75
Pak, V. S.	TPI	SWI	1974-76
Panchenko, V. P.	IAE	MHD	1974-75
Panchenko, N. N.	YEF	SWI	1974-75
Pavlov, Ye. P.	YEF	SWI	1974-75
Pavlovskiy, A. I.	---	HEF	1974-76
Perezhirov, Yu. I.	TPI	MUL	1971-73
Pichugin, V. V.	IAE	EMG, SWI	1974-75
Pinchuk, A. I.	AEM	SWI	1973-75
Pinus, V. K.	AEM	SWI	1974-75

Name	Institute	Research Area	Years
Pishchikov, S. I.	IHT	MHD, SES	1973-75
Polyanskiy, L. Ye.	---	SWI	1975-76
Polyudov, V. V.	---	MHD	1972-74
Popkov, O. V.	IHT	SES	1970-72
Potekhin, S. P.	YEF	SWI	1974-75
Pryanikova, G. A.	---	SWI	1974-76
Razin, A. A.	---	SWI	1972-74
Remnev, G. Ye.	TPI	SWI	1975-76
Romanov, Yu. A.	TPI	MUL	1970-73
Royfe, I. M.	YEF	SWI	1974-75
Rozhdestvenskiy, B. V.	YEF	SES	1973-75
Rudenko, A. A.	YEF	SWI	1974-75
Rudenko, N. S.	TPI	SWI	1974-76
Rutkevich, I. M.	---	HEF	1966-68
Ryukkert, V. V.	---	SWI	1974-76
Sabanskiy, I. I.	YEF	SES	1973-75
Savrov, S. D.	IHT	MHD	1968-70
Semchenko, V. V.	IME	SWI	1974-75
Semenov, V. N.	IAE	EMG	1974-75
Seredenko, Ye. V.	YEF	SWI	1974-75
Sergeyenkov, B. N.	IHT	SES	1970-72
Sergeyev, V. F.	TPI	MUL	1970-73
Shatanov, A. A.	TPI	SWI	1975-76
Shcherbakov, A. P.	LPI	EMG	1970-75
Shelkov, Ye. M.	IHT	MHD, SES	1973-75
Sherstyuk, A. G.	MAI	HOM	1966-75
Sheyndlin, A. Ye.	IHT	MHD	1966-70
Sheynkman, V. S.	IHT	SES	1970-72
Shipuk, I. Ya.	IAE	EMG, SWI	1974-75
Shirochin, L. A.	YEF	SWI	1974-75
Shkuropat, P. I.	LPI	SWI	1974-76

Name	Institute	Research Area	Years
Shneyerson, G. A.	LPI	EMG	1961-75
Shutov, V. L.	LPI	SWI	1975-76
Shvetsov, G. A.	---	MHD	1972-75
Silin, V. P.	YEF	SWI	1974-75
Sipaylov, G. A.	TPI	MUL	1964-75
Skripunov, V. N.	YEF	SWI	1974-75
Smetanin, V. I.	TPI	SWI	1974-76
Smirnov, I. V.	---	SWI	1974-76
Smirnov, S. A.	---	SWI	1974-76
Smirnov, Ye. N.	---	HEF	1974-76
Sobko, E. I.	TPI	MUL	1972-74
Sobolev, O. P.	NPI	HEF	1967-69
Spevakova, F. M.	YEF	EMG, SES SWI	1973-75 1974-75
Spirchenko, Yu. V.	YEF	EMG	1973-75
Stekol'nikov, B. A.	YEF	SWI	1974-75
Stolov, A. M.	YEF	SWI	1974-75
Sukhorukov. A. G.	IHT	SES	1970-72
Suvorov, V. N.	---	HEF	1974-76
Svin'in, M. P.	YEF	SWI	1973-75
Sychev, V. V.	IHT	MHD, SES	1964-75
Ternovskiy, F. F.	IHT	SES	1965-73
Timonin, A. M.	YEF	EMG	1971-73
Titov, V. P.	---	MHD	1972-74
Tovma, V. A.	IHT	SES	1970-72
Trapeznikov, V. N.	---	SWI	1975-76
Troitskiy, S. R.	MAI	HOM	1965-67
Trokhachev, G. V.	YEF	SES	1973-75
Tsareva, L. S.	IAM	HEF	1968-70
Tsitsiashvili, S. S.	---	SWI	1974-76
Tsvetkov, V. I.	TPI	SWI	1974-76

Name	Institute	Research Area	Years
Ulnich, F. R.	IAE	SWI	1974-75
Uralov, S. N.	YEF	SWI	1974-75
Usov, Yu. P.	TPI	SWI	1975-76
Utyugov, Ye. G.	IAE	EMG, SWI	1974-75
Velikhov, Ye. P.	IAE	MHD	1973-75
Vitshas, A. F.	IAE	MHD	1966-68
Volkov, Yu. M.	IAE	MHD	1974-75
Voytenko, A. Ye.	NPI	HEF, SWI	1967-74
Yablochnikov, B. A.	NPI	HEF	1972-74
Yagnov, V. A.	IAE	SWI	1974-76
Yakovlev, V. A.	---	SWI	1974-76
Yakushev, A. A.	IAE	MHD	1974-75
Yarysheva, M. D.	LPI	SWI	1975-76
Yefimov, B. V.	LPI	SWI	1975-76
Yegorov, S. A.	YEF	SES	1973-75
Yegoshkina, L. A.	MAI	SES	1969-75
Yudakov, Yu. V.	YEF	SES	1973-75
Yurchenko, V. I.	NPI	EMG	1972-75
Yurinov, V. M.	LPI	HOM	1965-75
Zablotskaya, G. R.	YEF	EMG	1973-75
Zaklyaz'minskiy, L. A.	IHT	MHD	1970-72
Zenkevich, V. B.	IHT	MHD, SES	1964-75
Zheltov, V. A.	YEF	EMG	1973-75
Zhemchugov, G. A.	MAI	SES	1968-70
Zherebnenko, V. I.	NPI	SWI	1973-75
Zlobina, O. A.	LPI	HOM	1974-75
Zolotarev, E. I.	---	SWI	1975-76
Zotova, Ye. A.	IAE	EMG	1973-75
Zubkov, P. I.	NPI	SWI	1969-74
Zykov, A. P.	---	SWI	1972-74

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